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Selective Catalytic Reduction Urea Infrastructure Study

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Acronyms and Abbreviations

ADL	Arthur D. Little
CARB	California Air Resources Board
DI	deionized
DOE	U.S. Department of Energy
DOT	Department of Transportation
DPF	diesel particulate filters
ECU	electronic control unit
EGR	exhaust gas recirculation
EIA	DOE Energy Information Administration
EPA	U.S. Environmental Protection Agency
FHWA	DOT Federal Highway Administration
GDP	gross domestic product
GHG	greenhouse gasses
GVWR	gross vehicle weight rating
HHDV	heavy heavy-duty vehicle
LDT	light-duty truck
LHDT	light heavy-duty truck
MDPV	medium-duty passenger vehicle
MDT	medium-duty truck
MPR	monthly progress report
MSDS	materials safety data sheet
MY	model year
NMHC	non-methane hydrocarbons
NOx	nitrogen oxides
NREL	National Renewable Energy Laboratory
NSR	nitrogen stoichiometric ratio
ORNL	Oak Ridge National Laboratory
PM	particulate matter
RO	reverse osmosis
SCR	selective catalyst reduction
SNCR	selective non-catalytic reduction
TS&D	transportation, storage, and distribution
VIUS	vehicle inventory use survey

The U.S. Department of Energy (DOE) is assessing viable exhaust after-treatment technologies for heavy- and light-duty diesel engines. Selective catalytic reduction (SCR) is one technology being developed to reduce NO_x emissions to meet new, more stringent heavy- and light-duty vehicle emission standards. A key component of implementing SCR technology is supplying and distributing urea as the ammonia reductant. Arthur D. Little was selected by the National Renewable Energy Laboratory (NREL) to assess the potential demand for urea, the cost of the associated production and distribution infrastructure, and the environmental impacts related to the use of SCR-urea.

Urea, which its manufacturers consider a stable and safely transportable means of providing ammonia to SCR catalysts, is produced by combining ammonia and carbon dioxide at high pressure. Several grades of urea currently are produced. The most common form is agricultural grade urea, which is widely used as a fertilizer. Industrial grade and reagent grade urea are used in the manufacturing and chemical industries. Some urea grades contain impurities that may adversely affect SCR, other emission control devices, or urea pumps and injectors. Reagent grade urea typically contains the least biuret (a sub-product of urea), heavy metals, and conditioners and may be a good candidate to be blended with water to a 32.5% by weight solution, which is the preferred urea concentration because it has the lowest freezing point. However, the industry has yet to determine the exact urea composition to meet SCR operational requirements. Additional collaborative studies are needed to further develop an SCR-urea specification.

Demand

Annual urea demand in the United States ranges between 9 and 10 million short tons (tons) per year and comes mainly from the agricultural sector (85% of total demand). Total domestic production is 6 million tons per year, about 60% to 65% of manufacturing capacity. Whether the domestic demand is met with domestic or foreign urea depends greatly on the domestic and world price of natural gas, since natural gas is the principal feedstock for urea. Worldwide demand is estimated at 100 million tons per year, compared to a production capacity of 133 million tons per year. Thus, there is excess urea production capacity both nationally and worldwide. Increasing the production of reagent grade urea may not require production infrastructure modifications because all urea grades are produced from the same highly concentrated urea melt. If a more pure urea is required, a segregated production infrastructure may be needed, requiring a significant investment.

Fuel consumption and vehicle population growth projections by the DOE and the U.S. Department of Transportation (DOT) indicate that on-road urea demand (for heavy- and light-duty vehicles) could reach 200,000 tons per year in 2007 and 700,000 tons per year in 2010. SCR-urea consumption is directly related to the SCR systems' urea-to-fuel use ratio. This estimate is based on a conservative demonstrated ratio of 1 gallon of urea per

18 gallons of diesel consumed. Agricultural urea consumption is expected to remain stable through 2010, while industrial use could vary with industrial sector growth. In the near future, urea may be increasingly used to supply SCR and selective non-catalytic reduction (SNCR) NO_x control systems for stationary sources. Based on the potential amount of NO_x to be reduced from stationary sources, the incremental stationary SCR-urea demand in 2010 could total 5.4 million tons per year, several times more than the on-road SCR-urea demand. This potential growth may further assist in developing an SCR-urea infrastructure.

The current urea distribution infrastructure consists of a network of plants and distribution terminals located throughout the nation. Although urea manufacturing plants are located mostly in the Gulf States and the Midwest, agricultural and petroleum product distribution terminals are present in all regions. It is expected that the SCR-urea distribution pathways will be similar to current urea and diesel distribution pathways. The extent to which existing infrastructure will be used to transport and store SCR-urea depends on the purity requirements of the SCR systems.

Infrastructure Cost

To analyze the infrastructure requirements, life-cycle cost, and greenhouse gas emissions, nine production and distribution pathways were developed that include all potential combinations of production location, storage location, transportation mode, blending to 32.5% solution location, and dispensing location. Infrastructure requirements include blending equipment, storage, and dispensing infrastructure at the retail location. Retail locations include truck stops, service stations, and fleet stations.

The life-cycle cost of five cases based on foreign and domestic urea pathways and representing the cost envelope were analyzed. The costs of producing and distributing SCR-urea were estimated separately. Based on the distribution pathways developed, the distribution cost can range from $0.70 to $35 per gallon, depending on the assumptions about SCR-urea demand, the number of retail points, and the level of product segregation. The lower end of the range assumes high throughput truck stops, while the upper part of the range represents light-duty retail outlets with low throughput of urea. Production costs are estimated to range between $0.12 and $0.30 per gallon of SCR-urea, and an estimated $0.05 to $0.10 per gallon can be added to the cost when SCR-urea is sold. Dispensing costs represent the majority of the estimated distribution cost along the assumed pathways.

Environmental Impacts

Since significant agricultural urea production facilities and extensive distribution pathways exist today, it is anticipated that SCR-urea will not have significant incremental environmental impacts in terms of spills. In general, urea degrades quickly in soil, water, and air. Ingested or absorbed in large quantities, it can be hazardous to plant and animal life. Clean-up options are well established and can be updated to accommodate new locations where urea will be used, such as retail fueling stations.

Using SCR-urea could increase greenhouse gas life-cycle emissions related to diesel use by up to 1% compared to a heavy-duty diesel vehicle baseline.

The infrastructure needed to support the implementation of SCR in heavy- and light-duty diesel vehicles may be based, at least in the short- and mid-term, on the current urea infrastructure. The purity requirements for SCR-urea could dictate the extent to which the existing infrastructure will be used to produce, store, and transport SCR-urea. The major infrastructure components to be developed relate to blending and dispensing SCR-urea at retail stations. The retail cost of urea is mostly dependent on the number of retail stations at which SCR-urea is expected to be available. In addition to an SCR-urea specification, other issues to be researched further include the long-term involvement of traditional urea producers in the SCR-urea market, retail station logistics, the effects of SCR-urea on diesel vehicle life-cycle costs, and life-cycle criteria pollutant emissions.

1. Introduction/Background

Between 1997 and 2000, the U.S. Environmental Protection Agency (EPA) set new Federal emission standards for on-road diesel vehicles that will dramatically reduce allowable nitrogen oxide ($NO_{x)}$ and particulate matter (PM) emissions. Under these new standards, model year 2004 (MY2004) NO_x emissions from on-road heavy-duty diesel engines will be half those required under MY1998 standards. Starting with MY2007, new on-road heavy-duty diesel engines will need to achieve phased-in NO_x and PM levels that are only 10% of MY2004 levels. As a result, diesel engine and vehicle manufacturers will need to implement exhaust aftertreatment control devices to meet the MY2007 and later (MY2007+) requirements. These standards will be implemented in conjunction with Federal low-sulfur diesel (<15-ppm sulfur) production requirements; facilitating the introduction of low-emission technologies that would otherwise be compromised by high sulfur levels in the diesel engine exhaust. The following sections provide a detailed explanation of the new emission standards and their implications for future heavy- and light-duty diesel engines.

1.1 The Heavy-Duty Engine Standard

Under the current federal emissions standards, all new heavy-duty diesel on-road engines sold in the United States must be certified to emit no more than 4.0 g/bhp-hr of NO_x, 0.1 g/bhp-hr PM, and 1.3 g/bhp-hr of non-methane hydrocarbons (NMHC) when tested on the Transient Federal Test Procedure engine dynamometer cycle.[1] Heavy-duty vehicles are defined as all vehicles above 8,500 pounds gross vehicle weight rating (GVWR).[2]

As shown in Table 1-1, the federal emission standards require engine manufacturers to reduce their NO_x, and NMHC emissions in new MY2004-2006 on-road heavy-duty diesel engines by about half. However, under consent decrees signed in 1998 by EPA and several heavy-duty diesel engine manufacturers, most heavy-duty diesel engine manufacturers agreed to meet the MY2004 standards starting October 2002. It is expected that most manufacturers will achieve the MY2004 NO_x standards by developing exhaust gas recirculation (EGR) systems. Diesel particulate filters (DPF) or diesel oxidation catalysts may be used to control the increased PM emissions due to the EGR systems.

For MY2007 and beyond, the federal emissions standards for new on-road heavy-duty diesel engines will require much tighter emission controls. While compliance with the 0.01 g/bhp-hr PM standard begins with MY2007 engines, the NO_x 0.2 g/bhp-hr and 0.14 g/bhp-hr NMHC standards are implemented in 2 phases over 4 model years as presented in Table 1-2. To achieve the additional exhaust treatment necessary to meet the NO_x reduction required by the MY2007+ federal on-road heavy-duty engine emission

[1] As an option, complete heavy-duty diesel vehicles under 14,000 lbs. GVWR may be chassis certified.

[2] Starting with MY2004, vehicles between 8,501 and 10,000 lbs. GVWR, inclusive that are used for personal transportation are subject to the Tier 2 standards, not the MY2004+ heavy duty vehicle standards.

standards, manufacturers are planning to use advanced emission control devices, as discussed in Section 1.3.

Table 1-1. Federal Emission Standards for On-Road Heavy-Duty Diesel Engines (g/bhp-hr)[3]

	MY1998-2003	MY2004-2006	MY2007 and Later [b]
NO_x	4.0	2.5[a]	0.2
PM	0.1	0.1	0.01
NMHC	1.3	(0.5)[a]	0.14

[a] The standard is 2.5 g/bhp-hr NO_x + NMHC.
[b] The MY2007 and later standard is phased in at a 50% rate over four years and allows higher certification levels during those years.

Table 1-2. MY2007+ On-road Heavy-duty Engine NO_x + NMHC Standards Phase-in Schedule[4]

Model Year	Requirements
2007	50% of all MY 2007 engines sold
2008	50% of all MY 2008 engines sold
2009	50% of all MY 2009 engines sold
2010+	100% of all MY 2010 engines sold

1.2 The "Tier 2" Federal Light- and Medium-Duty Diesel Vehicle Emissions Standard

Federal Tier 2 emission standards will require vehicle manufacturers to reduce their NO_x, PM, and NMHC emissions in on-road MY2004-2007 light- and medium-duty vehicles to the levels shown in Table 1-3. Light-duty vehicles are defined for the purposes of this rule as all vehicles below 8,500 lbs. GVWR. If used for personal transportation, vehicles between 8,501 and 10,000 lbs. GVWR, inclusive, are classified as medium-duty passenger vehicles (MDPVs). If a MY2004+ vehicle is between 8,501 and 10,000 lbs. GVWR, inclusive, and is not used for personal transportation, it is subject to the MY2004+ federal on-road heavy-duty vehicle standards.

Tier 2 standards will apply to all light-duty vehicles and MDPVs regardless of weight or fuel type; manufacturers are offered a choice of certification levels, with a maximum fleet average of 0.07 g/mile NO_x at full useful life (120,000). The Tier 2 standards will be phased in by vehicle class as shown in Table 1-4. Manufacturers are currently

[3] Environmental Protection Agency, Office of Transportation and Air Quality, www.otaq.epa.gov
[4] Environmental Protection Agency, Office of Transportation and Air Quality, www.otaq.epa.gov

researching and developing aftertreatment control technology to meet the federal requirements. Section 1.3 presents some of the most promising options.

Table 1-3. Federal Emission Standards for Light- and Medium-duty Diesel Vehicles: Tier 2 (g/mi) [a]

	Tier 2: MY2004+[c]	
	50,000 miles	**120,000 miles**
NO_x	0.05-0.1	0.00-0.20 (0.07 fleet average)
PM	—	0.00-0.02
NMOG (Tier 2)	0.075-0.100	0.00-0.125

a Values shown reflect range of vehicle weight categories. Temporary bins with higher allowances for heavier vehicles (not shown in ranges) expire after MY2008.

b As many as 11 bins are available for certification. Tier 2 specifies PM or NMOG levels for the bins, but allows the fleet levels to change with mix needed to meet the fleet average.

Table 1-4. MY2007+/Tier 2 Standards Phase-in Schedule[5]

Model Year	Vehicles Meeting Tier 2 Standards
2007	All passenger cars and light light-duty trucks
2008	All passenger cars and light light-duty trucks; some heavy light-duty trucks and medium-duty passenger vehicles
2009 +	All light-duty vehicles sold

1.3 Advanced Emission Control Technologies

In order to meet the greatly-reduced future on-road diesel vehicle emission standards, most manufacturers are expecting to implement one or more of the emission control technologies presented in Table 1-5. The NO_x and PM control devices listed in Table 1-5 are at various levels of development and demonstration. Some devices are "verified" to provide emission reductions by EPA and/or the California Air Resources Board (CARB). Verification programs are an accelerated certification for retrofit devices, which include limited emission and durability testing. In addition to varied levels of NO_x and PM efficiency, these devices have different operational requirements (e.g., differing reagent or reductant requirements) and impacts on fuel economy.

[5] Environmental Protection Agency, Office of Transportation and Air Quality, www.otaq.epa.gov

Selective Catalytic Reduction (SCR) is a promising technology with the potential to achieve large NO_x and some PM reductions. SCR has been used to control stationary source NO_x emissions for over twenty years. It is currently being demonstrated in mobile diesel applications both in Europe and in the United States. The following section describes SCR technology for on-road diesel engines.

Table 1-5. Status of Emission Control Devices Research, Development, and Demonstration [6]

Emission Control Device	Description	Typical/ Expected NO_x Efficiency	Typical/ Expected PM Efficiency	Status
NO_x Adsorber	Adsorbs NO and oxygen during lean operation, uses CO and HC from periodic rich operation to convert to N_2	>80%	30%	In development; available in 2007
Diesel Particulate Filter	Collects particles in diesel exhaust	None	80 to 90%	Verified for some heavy-duty engines model year and duty cycles in CA
Oxidation Catalyst	Oxidizes HC and CO in exhaust	None	20 to 30%	In commercial use in bus engines; not verified for non-bus heavy-duty vehicles
Selective Catalytic Reduction Catalyst	Converts NO_x to N_2 and O_2 in presence of ammonia, or ammonia-carrying agent (e.g., urea)	>80%	30%	In development /demonstration; Available 2005-2007. Requires reductant dispensing and storage infrastructure
Non-thermal Plasma	High energy electrons convert exhaust pollutants to inert species	>65%	30%	In demonstration phase for light-duty only; in development for heavy-duty applications

1.4 Selective Catalytic Reduction (SCR) Systems

SCR systems for vehicles require an on-board supply of ammonia or other nitrogen-containing chemicals, such as urea, that decompose into ammonia in the engine exhaust stream. The following Equations 1-1 and 1-2 describe how the SCR catalyst functions. Ammonia (NH_3) reacts with NO and NO_2 to produce N_2 and water. If the reductant used is urea [$(NH_2)_2$ CO], it is first hydrolyzed to produce ammonia (Equation 1-3).

$$4\ NO + 4\ NH_3 + O_2 \xrightarrow{\text{Catalyst}} 4\ N_2 + 6\ H_2O \qquad (1\text{-}1)$$

[6] Arthur D. Little, "NO_x Emission Reduction Technology Status and Solutions," October 2001.

$$6\ NO_2 + 8\ NH_3 \xrightarrow{\text{Catalyst}} 7\ N_2 + 12\ H_2O \qquad (1\text{-}2)$$

$$(NH_2)_2CO + H_2O \longrightarrow CO_2 + 2\ NH_3 \qquad (1\text{-}3)$$

Figure 1-1 is a schematic of an on-board vehicle SCR system. While exhaust gas from the engine is flowing through the catalyst, urea stored in a tank is injected into the pre-catalyst exhaust. The electronic control unit (ECU) meters the urea injection rate.

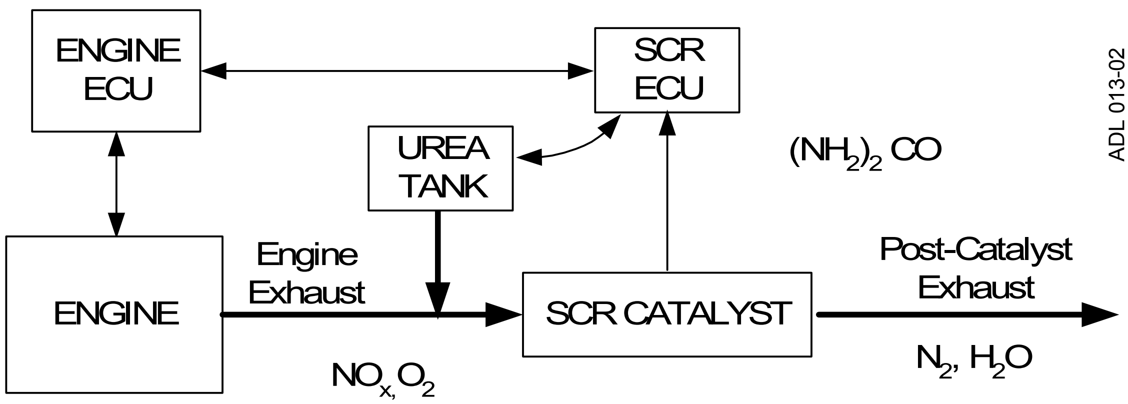


Figure 1-1. Schematic of SCR Catalyst in Vehicle Application[7]

In order to optimize the emission reductions, manufacturers are developing SCR systems combining several emission control devices. Figure 1-2 is an example of such a system. In this case, the oxidation catalyst oxidizes exhaust hydrocarbon and CO emissions, as well as converts NO to NO_2. The PM filter traps and oxidizes the particulate matter emissions in an NO_2 rich environment. The NO_2 is reduced to N_2 on the SCR catalyst. The NH_3 slip catalyst is placed after the SCR catalyst to limit the amount of unreacted ammonia in the post-catalyst exhaust.

[7] Figure based on Miller, *et al.*, “The Development of Urea-SCR Technology for U.S. Heavy Duty Trucks,” SAE 2000-01-0190.

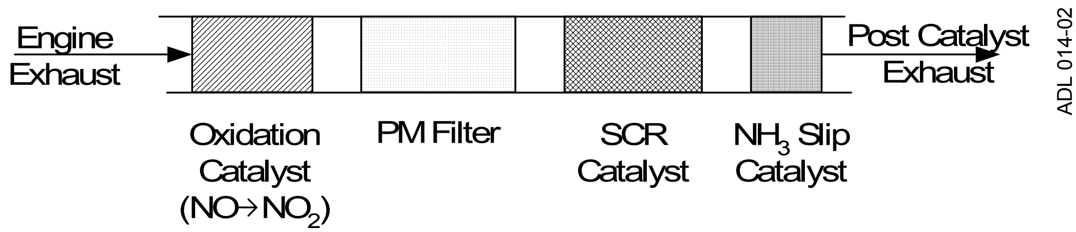


Figure 1-2. Example of a Mobile SCR System Configuration[8]

Storing ammonia on-board may pose several challenges including corrosion and health hazards. Therefore, vehicle SCR systems are being developed with urea [$(NH_2)_2$ CO] as the reductant. Most vehicle SCR system demonstrations to date have used urea in 32.5% by weight solution as a reductant. Using a urea solution offers a means for generating ammonia for the SCR system while significantly reducing the health and corrosion issues. Urea is widely used as a fertilizer and as a precursor chemical for many plastics. Urea is also used in stationary SCR systems as a reductant. While a very well-established infrastructure is present for distributing urea to meet existing demand, no infrastructure is in place for distributing mobile SCR urea. This report addresses the important elements for distributing urea for mobile SCR systems.

1.5 Study Approach

The objective of this study is to estimate the potential demand for urea, the cost of the associated production and distribution infrastructure, and assess the environmental impacts related to the use of SCR-urea. These objectives are reflected in the five tasks defined in the scope of work presented in Table 1-6.

The project work was initiated by a kick-off meeting to allow the client and other observers an opportunity to provide input and comments on the ADL work plan. Monthly progress reports (MPRs) and project review meetings allowed feedback as work progressed.

[8] Figure based on Chandler, *et al.*, “An Integrated SCR and Continuously Regenerating Tap System to Meet Future NO_x and PM Legislation.” SAE 2000-01-0188.

Table 1-6. Scope of Work Summary

Task	Description
1. Selection of Pathways	• Develop realistic pathways for manufacturing and distributing of SCR-urea based on industry input
2. Projection of Reductant (Urea) Consumption	• Estimate the total consumption of urea by vehicle type • Determine the number of manufacturing sites, distribution sites, and retail sites required for the United States for each pathway
3. Estimate of Capital Requirements and Retail Costs	• Assess the capital requirements for new equipment needed to manufacture and distribute urea reductant • Determine life-cycle urea cost estimates based on operating costs during manufacturing and distribution
4. Environmental Impacts of Spills	• Identify potential spill sizes, clean-up options, and potential air and water impacts at each point of the pathway
5. Life-cycle Greenhouse Gas Emission	• Estimate life-cycle greenhouse gas and other emissions for each pathway

ADL contacted various industry participants, including urea manufacturers and distributors, to determine current availability of SCR-compatible urea and existing urea pathways. The results of this research are presented in Section 2, Urea Production and Specifications for Use in On-road SCR Systems.

Based on published data, ADL estimated urea demand and current production levels. Based on projected fuel consumption, ADL estimated the amount of urea required to implement SCR in all on-road diesel vehicles meeting federal model year 2007+ emission standards. Section 3, Urea Production and Demand, summarizes these findings.

The previous sections provided the basis for developing a most likely pathways scenario. These pathways are discussed in Section 4, Selection of SCR-Urea Distribution, Storage, and Transportation Pathways. Section 5, Production and Distribution Life-Cycle Cost, presents a range of estimated costs for implementing an SCR-urea distribution infrastructure.

Section 6, Environmental Impact of Urea Use, presents the environmental and health impacts from the use of SCR-urea. Section 7, Life-Cycle Greenhouse Gas Emissions, presents pathway specific life-cycle greenhouse gas emissions associated with SCR-urea production and distribution infrastructure.

Section 8, Conclusions, presents conclusions on the implications of the development of an SCR-urea infrastructure to meet future emission regulations.

2. Urea Production and Specifications for Use in On-road SCR Systems

Urea is an attractive reductant choice for on-road SCR as it is less corrosive and poses a lower health and safety risk than ammonia, yet readily decomposes into ammonia at the high temperatures typical for engine exhaust[9]. Commercially available urea comes in three main types: agricultural, industrial, and high-purity reagent grade urea. All urea grades start as a concentrated urea melt, as the manufacturing process used to create the melt is common to all grades. The concentrated urea is then modified, as needed, to create the specific commercial grades. Such modifications include introducing additives that facilitate transport and end-use[10].

This section will discuss the differences between the various commercially available urea grades. It will also discuss which urea grade or grades are likely to be compatible with the impurity thresholds of on-road SCR systems. This section will conclude with a discussion of urea quality issues that require further study.

2.1 Urea Production Process

Urea is formed by combining ammonia and carbon dioxide at high pressure to form ammonium carbamate (1):

$$2NH_3 + CO_2 \Leftrightarrow NH_2COONH_4 \tag{2-1}$$

Although equation 2-1 represents an equilibrium process, the reaction is driven nearly to completion in industrial processes. The ammonium carbamate formed via equation 2-1 is dehydrated by adding heat to form urea and water:

$$NH_2COONH_4 \Leftrightarrow CO(NH_2)_2 + H_2O \tag{2-2}$$

Equation 2-2 does not fully achieve completion, so excess ammonium carbamate is recovered for reuse. Once the urea solution is separated from residual ammonium carbamate and passed through evaporators to remove most of the water, the highly concentrated urea melt (95 to 99.7 percent urea) is then processed for distribution. This final phase of urea production involves processing the urea into either urea liquor (50 to 70 percent liquid urea by weight), prills (small drops of liquid urea that have been dried into spheres), or granules (drops of urea that are allowed to agglomerate as they dry)[11]. Figure 2-1 shows the major steps in the urea production and distribution process.

9 Miller, *et. al.*, "The Development of Urea-SCR Technology for US Heavy Duty Trucks." SAE #2000-01-0190. 2000.

10 U.S. Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors, AP-42, fifth Edition, Volume I, Fifth Edition." Section 8.2. 1995.

11 European Fertilizer Manufacturers Association, “Production of Urea and Urea Ammonium Nitrate, Booklet No. 5 of 8.” www.efma.org. 1997.

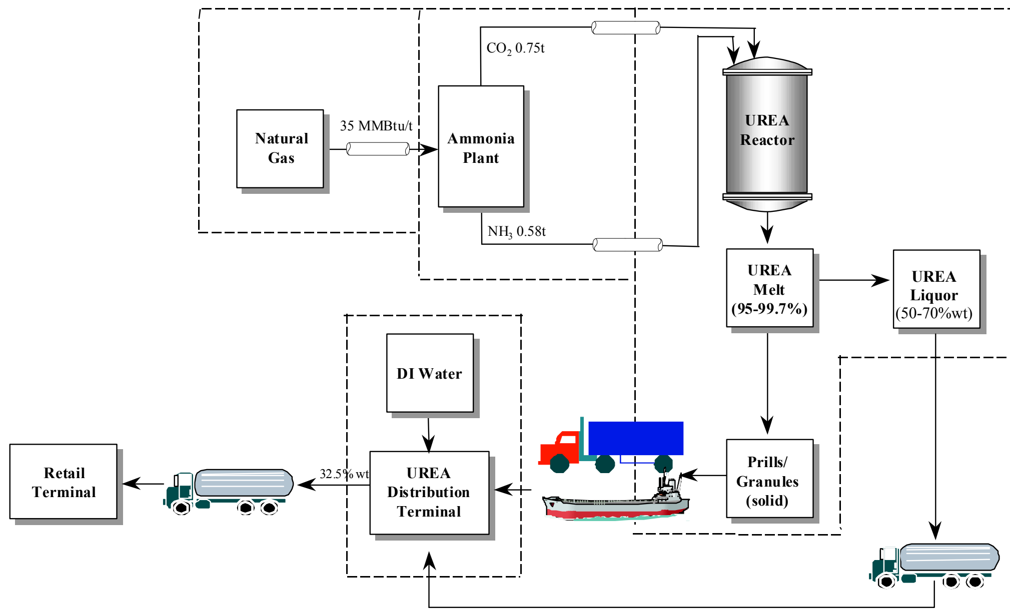


Figure 2-1. Example Urea Production and Distribution Pathways

Additives (such as conditioners tailored for enhanced end-use) and contaminants (such as trace metals, formaldehyde, and biuret) can be introduced into the urea solution through additional urea processing. For example, when urea solution is maintained at temperatures above 60°C (140°F)—as in the evaporator section—trace amounts of the urea decomposes into biuret and ammonia through the following reaction:[12]

$$2CO(NH_2)_2 \Rightarrow H_2NCONHCONH_2 + NH_3 \qquad (2\text{-}3)$$

Other contaminants—such as iron, copper, or other metals—can be introduced through contact with the process piping and transfer/transport equipment. Contaminants such as natural gas, ammonia, and carbon dioxide also may be present in trace amounts in the original feedstock.

2.2 Urea Grades

The urea production process described in Section 2.1 is used to produce three main commercial grades of urea: *agricultural grade* urea (which is primarily sold as solid prills or granules), *industrial grade* urea (sold as solid or liquid), and high-purity *reagent grade* urea (sold as solid or liquid). As indicated before, all urea grades are formed from a highly-concentrated urea melt. Urea producers create agricultural or industrial grade urea by adding conditioners that will enhance handling and end-use. In

[12] U.S. Environmental Protection Agency, "Urea Manufacturing Industry: Technical Document." EPA-450/3-81-001, January 1981.

comparison, reagent grade urea contains fewer, if any, additives. However, trace contaminants still are present in reagent grade urea.

The products available within each urea grade can also vary with respect to additive and contaminant composition. Tables 2-1 and 2-2 provide an example of commercial urea composition for solid forms.

Tables 2-1 and 2-2. Sample Composition of Commercially-Available Agricultural, Industrial, and High-Purity Reagent Grade Urea (Solid Forms)[13]

	Agricultural Grade	Industrial Grade
Form	Granular	Granular
Total Nitrogen (%)	46.0	46.0
Biuret Content (%)	1.2-1.4	1.3
Ash[a] (ppm)	50	60
Iron Content (ppm)	1-2	3
Conditioner (%)	0.3-0.5	1.5

[a]Phosphates and various metals.

High-Purity Reagent Grade[b]	
Form	Solid Crystals
Melting Point (°C)	132-135
Biuret Content (%)	0.0
Copper (ppm)	<0.5
Iron Content (ppm)	<0.5
Lead (ppm)	<0.5
Chloride (ppm)	<5.0
Sulfate (ppm)	<100

[b]Concentrations represented as less than a given number were below detectable limits. The detection limit is the number shown.

SCR systems will definitely be sensitive to some impurities. As shown in Tables 2-1 and 2-2, contaminants can be present in all urea grades. However, the impurities in reagent grade urea may be present only in trace amounts below standard detection limits, making reagent grade urea the purest of the three grades.

On-road SCR systems may require urea contaminant limits even lower than the levels indicated for reagent grade urea. If engine manufacturers using SCR systems determine that the contaminants present in reagent grade urea would be detrimental in concentrations lower than the detection limits reported above, more precise contaminant concentration evaluations should be performed. Manufacturers then could more accurately compare reagent grade urea specifications against contaminant threshold specifications for SCR systems and thereby determine if reagent grade urea is appropriate for on-road SCR. If lower urea contaminant levels are required, urea

[13] ADL communication with Jerry Weirs, BakerPetrolite, March 2001.

producers will need to implement additional contaminant control measures—such as using specially-coated urea transfer lines to avoid metal contamination from corrosion—in order to produce a specialized urea product that is compatible with on-road SCR systems.

2.3 Urea Specifications for Use in On-road SCR Systems

As discussed in Section 2.2, there are varying levels of impurities among the commercially-produced urea grades. SCR systems will not tolerate impurity levels found in some grades of urea. Urea contaminants, such as phosphates and metals, could plug or poison catalysts downstream of the urea injection point(s), reducing the available active area and thereby reducing device effectiveness.[14,15]

Urea Quality

In order to determine what SCR-urea specification is needed, ADL contacted engine and urea manufacturers. The manufacturers provided ADL with sample lists of "ideal" on-road SCR system urea contaminant thresholds, which indicated limits that were generally equal to or more restrictive than the specifications for reagent grade urea (see Table 2-3). At the same time, these manufacturers also indicated that it is currently difficult to manufacture a urea product on a large scale that reliably meets all of these suggested "ideal" contaminant levels. As a result, engine and urea manufacturers have been working together to develop a urea specification for on-road SCR systems that will be mutually acceptable.[16]

Continued testing and development may help identify additional compounds, if any, found in urea that are detrimental to SCR systems in the long-term.[17] Manufacturers' continued research and development may also lead to enhanced emission control systems that are more tolerant of impurities and thus less restrictive on urea quality. However, until more tolerant emission control systems can be developed that make use of a readily available urea product, urea and engine manufacturers will need to continue their collaboration to ensure a proper specification is developed and made available.

[14] Koebel, M., *et. al.*, "Recent Advances in the Development of Urea-SCR for Automotive Applications." SAE 2001-01-3625.

[15] Amom, B. and Keefe, G., "On-Road Demonstration of NOx Emission Control for Heavy-Duty Diesel Trucks using SINOx™ Urea SCR Technology – Long-term Experience and Measurement Results." SAE 2001-01-1931.

[16] ADL communication with Gary Keefe (Siemens) and Michael Knenlein (FuelTech); specific values are proprietary information.

[17] Amom, B. and Keefe, G., "On-Road Demonstration."

Table 2-3. “Ideal” Urea Grade for SCR Systems[18]

Property	Maximum Value	Property	Maximum Value
Alkalinity (%)	0.1	Zinc (ppm)	1.0
Calcium (ppm)	1.0	Chromium (ppm)	1.0
Magnesium (ppm)	1.0	Nickel (ppm)	1.0
Sodium (ppm)	1.0	Silicon (ppm)	2.0
Potassium (ppm)	1.0	Phosphate (ppm)	2.0
Iron (ppm)	1.0	Carbonate (%)	0.1
Copper (ppm)	1.0	Biuret (%)	0.3

Water Quality for Urea Solutions

Typically, on-road SCR systems use a 32.5% urea by weight solution in water.[19] However, some of the on-road SCR research papers reviewed for this study reported using urea solutions ranging from 30% to 40% by weight. [20,21] The 32.5% urea concentration provides the lowest crystallization point (-11°C or 14°F) of all possible urea in water concentrations.[22] For regions where urea freezing would be an issue, the urea storage tanks (both on-board and at dispensing stations) will require heating.

The water used to create the 32.5% urea solution can also introduce contaminants such as trace metals, minerals, or chlorine. In order to avoid introducing additional contaminants, de-ionized (DI) water has been used historically to achieve the target urea concentration for testing on-road SCR systems. However, varying levels of water purity can be achieved depending upon the type of DI system selected. Further study of this issue is needed to determine the optimal specification for the water used in urea blending.

2.4 On-road SCR-urea Specification Challenges and Barriers

The additives and contaminants that can be found in urea solution, whether they originate with the urea or the water used to create the solution, can interfere with SCR systems. Establishing SCR system contaminant thresholds for the various contaminants that may be present in urea would help minimize the occurrence of such interference.

[18] ADL communication with Michael Knenlein, FuelTech, April 30, 2002.

[19] Farshchi, M., *et. al*., “Dynamometer Testing of a Heavy Duty Diesel Engine Equipped with a Urea-SCR System.” SAE 2001-01-0516.

[20] Lambert, C., *et. al*., “Application of Urea SCR to Light-Duty Diesel Vehicles.” SAE 2001-01-3623.

[21] Koebel, M., *et. al*., “Recent Advances in the Development of Urea-SCR for Automotive Applications.” SAE 2001-01-3625.

[22] Miller, *et. al.,* “The Development of Urea-SCR Technology.” SAE 2000-01-0190.

Once SCR-compatible urea specifications are established, the appropriate urea grade can be identified—or developed, if needed—and implemented for on-road SCR use.

The vehicle, catalyst, and urea manufacturers are working together to create an appropriate urea specification. There is still some uncertainty within these industries as to what the ultimate on-road SCR-urea specification should be. These manufacturers have different requirements, are still developing the technology, and are still performing on-road testing for their products. Long-term testing may reveal contamination problems that have yet to surface. As a result, there is uncertainty about what specification should be used in the long term for on-road SCR-urea. However, in the near term, on-road SCR systems will need to use the most appropriate commercially available grade (*i.e.*, reagent grade urea) and/or specialized urea products.

3. Urea Production and Demand

In order to assess the viability of using urea as a reductant for SCR, ADL first determined how much urea is currently available in the domestic and world markets. ADL also determined urea demand from other traditional sources and the capacity of domestic and world production to support those demands. Based on these data, ADL projected the on-road SCR-urea demand through 2010. This analysis permits us to determine whether near-term SCR-urea demand can be met with existing domestic and world production capacity.

3.1 Current Urea Production and Demand

Currently, the majority of the urea consumed annually in the United States is used as fertilizer. Industrial users comprise the next largest group of urea consumers, as indicated in Figure 3-1, using urea to manufacture such products as resins, plastics, and polyurethane insulation. Urea in cattle feed comprises most of the remaining urea consumption in the U.S.

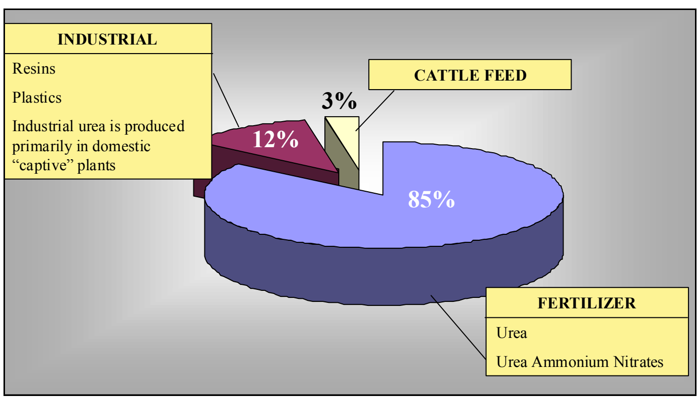


Figure 3-1. Current Urea Usage in United States by Category

The domestic demand for urea is primarily affected by changes in agricultural demand. Agricultural demand for fertilizer, and hence urea, fluctuates with season and type of crops planted. Crop choice is in turn affected by consumer demand and domestic/world prices.

In order to determine the viability of the various SCR penetration scenarios that may come into consideration, ADL determined the current urea production and urea production capacity for U.S. urea manufacturers. Using U.S. Census Bureau urea production data[23] in tandem with manufacturer's online reports, ADL determined that current U.S. urea production is about 6 million tons annually, or 60% to 65% of the nation's total rated manufacturing capacity (note that "tons" refers to short tons throughout this report). As a result, U.S. manufacturers may be able to accommodate an

[23] U.S. Census Bureau, "Current Industrial Reports." MQ325B(00)-4 [Fourth Quarter 2000]

additional 4 million tons of SCR-grade urea without expanding their infrastructure, assuming SCR-urea production would not require major plant modifications and assuming a constant demand for domestic urea from other sectors. Current U.S. urea production and capacity is shown in Table 3-1 for reference. As indicated in this table, the current worldwide urea production capacity exceeds current demand by over 30 million tons. Currently, about one-third of U.S. demand is met with imported urea, with a 10 million ton surplus of urea in the world market.

Table 3-1. Current Urea Production and Distribution

	All Urea Grades	Million Tons/Year
WORLD	Demand	100
	Production	110
	Capacity	133
DOMESTIC	Demand	9-10
	Production	6
	Capacity	10

Table 3-2. United States Production Capacity by Region

Key North American Urea Production Capabilities	
Manufacturer	**Capacity TPY**
PCS Augusta, GA; Geismar, LA; Lima, OH; Memphis, TN; Trinidad	1,826,000
CFI Donaldsonville, LA	1,700,000
Farmland[a]	2,670,000
Terra Industries Courtright, Ontario; Woodward, OK; Blytheville, AR; Port Neal, IA	715,000
Agrium Carseland, Calgary; Borger, TX; Ft. Saskatchewan, Saskatoon; Kenai, AK	2,279,000
Mississippi Chemicals Yazoo City, MS; Donaldsonville, LA	838,000
Total	10,028,000

[a]Most of the Urea produced is converted to UAN fertilizers at the Farmland factories.

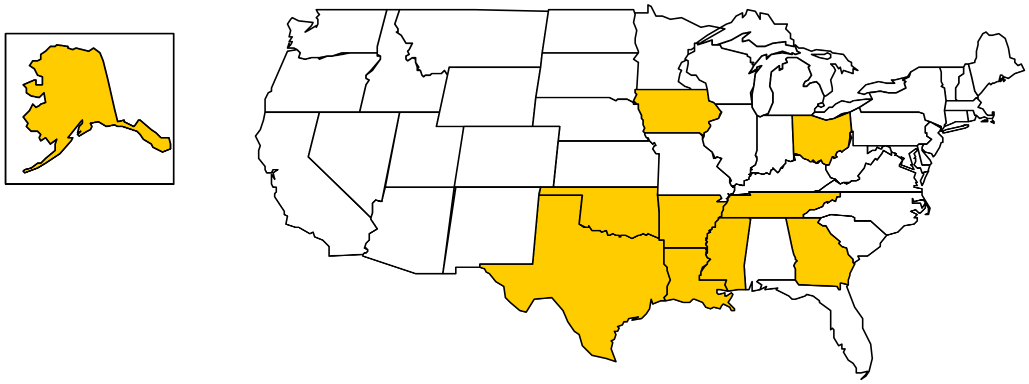


Figure 3-2. States with Key Urea Production Capabilities

As shown in Table 3-2 and Figure 3-2 below, most of the domestic urea production is focused in the southeastern United States, with some production in Iowa, Ohio, and Alaska. Domestic urea producers typically supply the domestic market with a mix of domestic and imported urea. Foreign urea is typically imported in solid form, without agricultural or industrial conditioners. When purchased by domestic distributors, urea producers process the imported urea by adding conditioners appropriate for the target end-user. The imported urea is then packaged and distributed to the domestic market in the same product stream as domestically produced urea.

Most imported urea comes from the Former Soviet Union, the Arab Gulf States, and Venezuela (see Figure 3-3). Additional imports originate in Canada and Trinidad from production facilities owned by U.S.-based urea manufacturers.

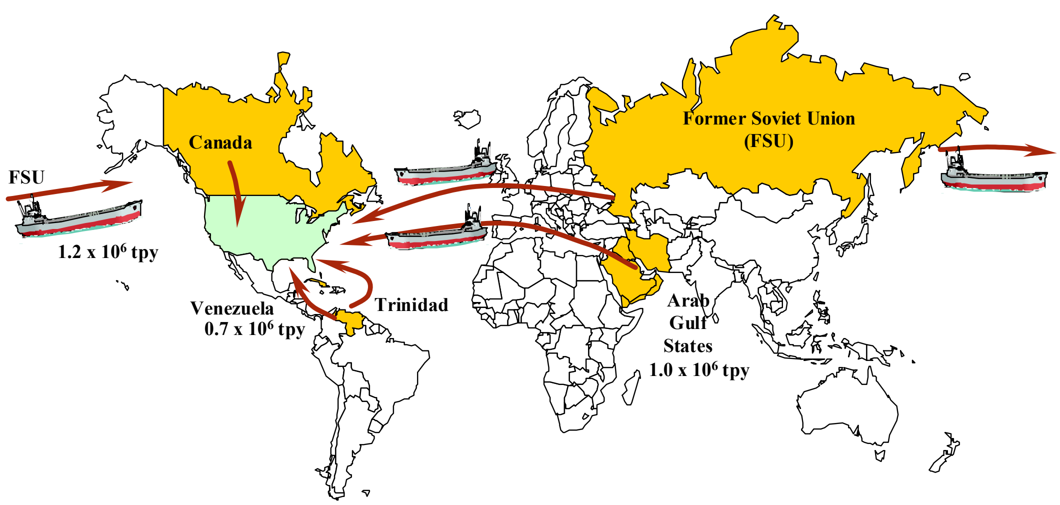


Figure 3-3. Foreign Urea Importation Pathways

3.2 Projected Urea Demand from Domestic On-road SCR

Domestic on-road SCR-urea demand was estimated by determining diesel fuel consumption by the projected SCR-equipped on-road vehicle fleet for years 2007 through 2010. The fuel consumption estimates were then used to estimate SCR-urea demand. The results are summarized in the following sections. ADL estimates indicate that U.S. urea production capacity would be sufficient to support on-road SCR systems for all SCR-equipped vehicles for the period studied.

3.2.1 Projected United States Diesel Fuel Consumption by On-road SCR-Equipped Vehicles

ADL determined the domestic diesel fuel consumption from all on-road vehicles by projecting the domestic diesel fuel consumption for years 2007-2010, and apportioning the consumption among the various vehicle weight classes. Then, assuming that all new on-road diesel vehicles using exhaust aftertreatment to meet emission standards for model years 2007-2010 will use SCR, ADL projected for each vehicle class the number of SCR-equipped vehicles sold each model year through 2010. By applying the fraction of on-road SCR-equipped vehicles out of a given vehicle class to the estimated vehicle class diesel consumption, ADL estimated the diesel consumption by on-road SCR-equipped vehicles for years 2007 through 2010.

Current and Projected Diesel Fuel Consumption

The DOE Energy Information Administration (EIA)[24] provides an estimate of transportation-based diesel fuel consumption for 1999 through 2020. EIA also provides specific consumption estimates for diesel-fueled light-duty vehicles, buses, and freight trucks. The DOT Federal Highway Administration (FHWA) Highway Statistics series provides additional 1992 and 1997 diesel vehicle population data for specific vehicle size classes, as well as state-specific fuel consumption, and was used to refine the EIA consumption estimates into more precise vehicle-size bins.[25]

The Oak Ridge National Laboratory (ORNL) Energy Data Book[26] and the DOT-FHWA Highway Statistics series provide on-road vehicle diesel consumption as determined from state diesel fuel sales tax reports. ADL calculated total on-road fuel consumption (both gasoline and diesel) for specific truck and bus sizes by using U.S. Census Bureau Vehicle Inventory Use Survey (VIUS) vehicle miles data and corresponding fuel economy data.[27] ADL also determined the percentage of miles driven by diesel trucks

[24] U.S. DOE Energy Information Administration, “Annual Energy Outlook 2001.” DOE/EIA-0383(2001). Tables 33 and 34.

[25] U.S. DOT Federal Highway Administration's Office of Highway Policy Information, “Highway Statistics,” 1992 and 1997. Table MF-2. “FHWA Highway Statistics” provides state diesel fuel data under the "Special Fuels" category, which includes a small amount of LPG sales and excludes most government, military, and exported sales.

[26] Oak Ridge National Laboratory for DOE, “Transportation Energy Data Book,” ORNL-6958. Table 2.8: "Highway Usage of Gasoline and Special Fuels, 1973-1997."

[27] U.S. Census Bureau, “1997 Economic Census, Vehicle Inventory and Use Survey.” EC97TV-US

and buses (as opposed to non-diesel vehicles) from U.S. Census Bureau VIUS data, and applied this percentage to each size category. State diesel consumption was provided by the FHWA-DOT Highway Statistics series.

On-road diesel consumption was assumed to increase linearly through 2010. Projections were obtained by linearly extrapolating ORNL Energy Data Book 1992-1997 diesel consumption values out to 2010.[28] This projection was compared with DOT FHWA Highway Statistics 1998-2000 on-road diesel consumption and DOE EIA projections for on-road medium- and heavy-duty diesel consumption. From these comparisons it was determined that a linear extrapolation provides values consistent with government agency projections (see Figure 3-4).

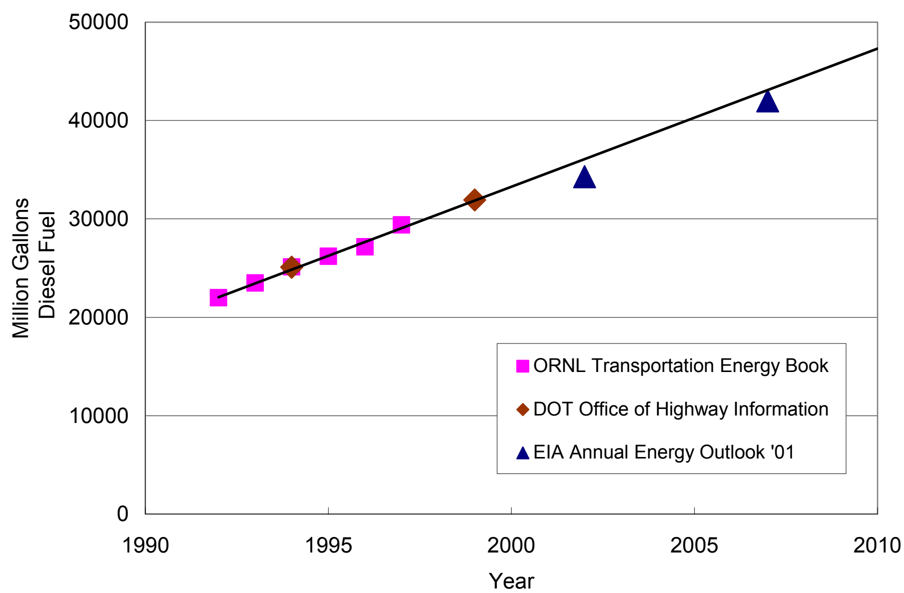


Figure 3-4. Projection of Domestic On-road Diesel Fuel Consumption

ADL also estimated the number of on-road diesel vehicles in the various weight classes as a reference point to determine future diesel consumption by vehicle class. ADL used U.S. Census Bureau VIUS data and assumed linear growth in each vehicle class population. The ratio of heavy heavy-duty vehicles to all diesel vehicles in the state-specific diesel fleet is assumed to be the same as nationwide.

Total U.S. and state-specific diesel fleet consumption data are available through the DOT-FHWA Highway Statistics series for each year through the present. These values are reported directly in Table 3-3. The U.S. Census VIUS provides information only for

[28] ORNL, “Transportation Data Energy Book.” ORNL-6985. Table 2.8: “U.S. Highway Special Fuels Consumption”.

trucks and buses, and is released every five years. Truck and bus fuel consumption for 1992 and 1997 was calculated by dividing the miles traveled for a given vehicle size group and fuel economy range by the fuel economy range, then summing the results over all fuel economy ranges. ADL estimated 2002 and 2007 consumption for each vehicle class by assuming diesel consumption will increase linearly through 2007. Table 3-3 summarizes the high-end (*i.e.*, most conservative) estimate of diesel consumption. The high-end diesel consumption estimate assumes that all vehicles reported in a given fuel economy range had the lowest-end fuel economy for that bin.

Table 3-3. Diesel Fuel Consumption by U.S. On-Road Diesel Vehicles (billion gallons)[29, 30, 31]

Vehicle Weight Class and/or Location	1992	1997	2002 (est.)	2007 (est.)
On-road vehicles	22	29	36	43
Light-duty trucks	1.4	2.0	2.7	3.3
Medium- and heavy-duty vehicles	21	27	33	38
Heavy heavy-duty vehicles (HHDVs)	20	25	30	35
California, Texas, and Northeast vehicles	6.8	8.6	10	12
California, Texas, and Northeast HHDVs	6.2	7.4	8.3	9.8

As shown in Table 3-3, heavy heavy-duty vehicles consume by far the most fuel — over 80% —of all diesel vehicles, thereby producing the most fleet emissions of all diesel vehicles. However, their total population comprises about 45% of all diesel vehicles, thus their per vehicle consumption factor is the greatest of all vehicle types. In order to determine the state-specific heavy heavy-duty (HHD) diesel vehicle consumption, ADL assumed that the proportion of HHD consumption to all on-road diesel vehicles was the same as for the whole United States.

In order to verify the accuracy of the linear growth assumption, the U.S. Census Bureau VIUS results were compared to data provided by ORNL and DOE EIA. For the ADL estimates, ADL chose to use values that were consistent with outside sources but which remained within the estimated production range of the U.S. Census Bureau VIUS-based analysis (see Table 3-4).

[29] Data for 1992 and 1997 obtained from FHWA "Highway Statistics," ORNL "Transportation Energy Data Book," and U.S. Census Bureau "VIUS," as previously referenced.

[30] Vehicle size for trucks and buses as defined in the U.S. Census Bureau, 1997 "VIUS:" Light-Duty Truck (avg. vehicle weight: 0-10000 lbs.), Medium-Duty (avw: 10000-19500 lbs.), Light-Heavy-Duty (avw: 19501-26000 lbs.), and Heavy-Heavy-Duty (avw.: over 26000 lbs.).

[31] Northeast states chosen: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont.

Table 3-4. Comparison of 2007 U.S. Diesel Fuel Consumption Estimates by Vehicle Weight Class and/or Location (billion gallons)[32]

Vehicle Weight Class and/or Location	ADL	U.S. Census Bureau VIUS	DOE ORNL	DOE EIA
On-road vehicles	43	—	43	42
Light-duty trucks	3.3	2.6-3.3	—	—
Medium- and heavy-duty vehicles	38	30-38	—	38
Heavy heavy-duty vehicles	35	23-35	—	—
California, Texas, and Northeast vehicles	12	10-14	12	—
California, Texas, and Northeast HHDVs	9.8	7.6-12	9.8	—

3.2.2 Estimation of Future SCR Vehicle Population and Fuel Consumption

Vehicle population projections from the EPA MOBILE model[33] were used to determine the estimated number of on-road diesel vehicles (including trucks, buses, and passenger vehicles) sold under the new emission standards (see Table 3-5). An estimated 667,000 new diesel vehicles will be sold in the United States in 2007, assuming a constant proportion of diesel to gasoline vehicles over time within each vehicle class and a 2% to 8% annual sales growth within each class. The projected new on-road vehicle diesel consumption for each vehicle class was determined by applying the fraction of new diesel vehicles in a vehicle class to the class' projected annual diesel fuel consumption (see Table 3-6).

Historical vehicle population data were provided by the U.S. Census Bureau VIUS. The projected vehicle population for 2007 and 2010 was determined by linear extrapolation from 1992 and 1997 VIUS data, and was compared with the EPA MOBILE model projections. Again, the portion of the total domestic diesel fuel consumed by each vehicle class was assumed to remain constant through 2010.

[32] Projections based upon data from DOE EIA "Annual Energy Outlook 2001," FHWA "Highway Statistics" series, ORNL "Transportation Energy Data Book," and U.S. Census Bureau "VIUS," as previously referenced.

[33] U.S. Environmental Protection Agency, Office of Mobile Sources, "Fleet Characterization Data for MOBILE6: Development and Use of Age Distributions, Average Annual Mileage Accumulation Rates and Projected Vehicle Counts for Use in MOBILE6." EPA420-R-01-047, September 2001.

Table 3-5. Projected New On-Road Diesel Vehicle Sales in the United States (thousand vehicles)[34, 35]

Vehicle Class	2007	2010
Passenger cars	6.7	6.2
Light-duty trucks	168	176
Medium-duty vehicles	94	99
Light heavy-duty vehicles	75	79
Heavy heavy-duty vehicles	322	338
Total vehicles	667	698

Table 3-6. Diesel Fuel Consumption by U.S. On-Road Vehicles in 2007 and 2010 (billion gallons)[36, 37]

Vehicle Class and/or Location	All Vehicles in 2007	New Vehicles Meeting MY2007+ Emission Standards in 2007	Vehicles Meeting MY2007+ Emission Standards in 2010
On-road vehicles	43	1.8	8.8
Light-duty trucks	3.3	0.1	0.2
Medium- and heavy-duty vehicles	38	1.6	8.4
Heavy heavy-duty vehicles	35	1.5	7.7
California, Texas, and Northeast vehicles	12	0.5	2.5
California, Texas, and Northeast HHDVs	9.8	0.4	2.1

34 US EPA, “Data for MOBILE6.” EPA420- R-01-047.

35 Vehicle size for trucks as defined in the U.S. Census Bureau, 1997 “VIUS:” Light-Duty Truck (avg. vehicle weight (avw): 0-10000 lbs.), Medium-Duty (avw: 10000-19500 lbs.), Light-Heavy-Duty (avw: 19501-26000 lbs.), and Heavy-Heavy-Duty (avw: over 26000 lbs.).

36 Projections made using data from FHWA “Highway Statistics” series, ORNL “Transportation Energy Data Book,” and U.S. Census Bureau “VIUS,” as previously referenced.

37 Northeast states chosen were: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont.

3.2.3 On-road SCR-Urea Consumption Projections

ADL estimated the amount of urea necessary for on-road SCR vehicles by estimating the future diesel fuel consumption by on-road vehicles meeting the Federal Tier 2 emissions standards (for on-road light-duty vehicles) and the Federal model year 2007 emission standards (for on-road heavy-duty vehicles). Assuming that all diesel vehicles meeting these emission standards are equipped with SCR systems, the estimated urea demand from on-road SCR systems is 0.2 million tons in 2007 (2% of the current domestic urea demand) and about 0.7 million tons in 2010 (7% of current domestic urea demand).[38]

Urea to Diesel Consumption Ratio

ADL determined urea demand from diesel consumption projections by assuming a baseline heavy-duty vehicle consumption ratio of 18 gallons of diesel fuel per one gallon of urea solution (32.5% urea by weight in water). Few references were available for on-road diesel SCR that contain this information, but one SAE study[39] indicated a heavy-duty vehicle in-use ratio of 18:1 up through 25:1, so ADL accepted the 18:1 ratio as a conservative estimate for all diesel vehicles.

A stoichiometric analysis was also performed in order to determine the theoretical limit to the amount of urea needed to provide the anticipated NO_x reduction. Assuming that the SCR catalyst is 100% efficient, that an oxidizing catalyst has converted all the NO_x to NO_2, and assuming a baseline vehicle fuel consumption efficiency and engine-out emission, the urea consumption ratio could reach as high at 50:1 for heavy-duty diesel vehicles, and 200:1 for light-duty diesel vehicles. Under different conditions, such as an advanced-design diesel engine that already produces little NO_x, the SCR system may require even less urea per gallon of diesel. See Appendix A for alternative urea to diesel consumption ratios for the light- and heavy-duty classes.

In the following analysis, ADL selected future diesel consumption values that appeared consistent among the various information resources, and used the baseline 18:1 consumption ratio to determine the amount of urea required for each vehicle weight class.

Urea Consumption from New Diesel Vehicles Nationwide

Assuming that a solution of 32.5% by weight solid urea dissolved in water will be used by on-road SCR systems, 1.5 tons of urea will be needed per thousand gallons of urea solution. Using the ratio of 18 gallons of diesel fuel to 1 gallon of urea solution

[38] Note that only 50% of the on-road MY2007-2009 heavy-duty engines sold are required to meet the MY2007+ standards (see Table 1-2). This study assumes that all those vehicles use SCR to meet the standards as a conservative estimate; other technologies may actually be employed in some of these vehicles.

[39] Miller, W.R., *et. al.*, "The Development of Urea-SCR Technology for US Heavy Duty Trucks," SAE 2000-01-0190.

described in the SAE paper by Miller, et. al.,[40] this implies 8.2 tons of solid urea will be required per 100,000 gallons of diesel fuel. ADL applied this factor to the diesel consumption estimates shown in Table 3-6 to determine on-road SCR-urea demand estimates for years 2007-2010 (see Figure 3-5).

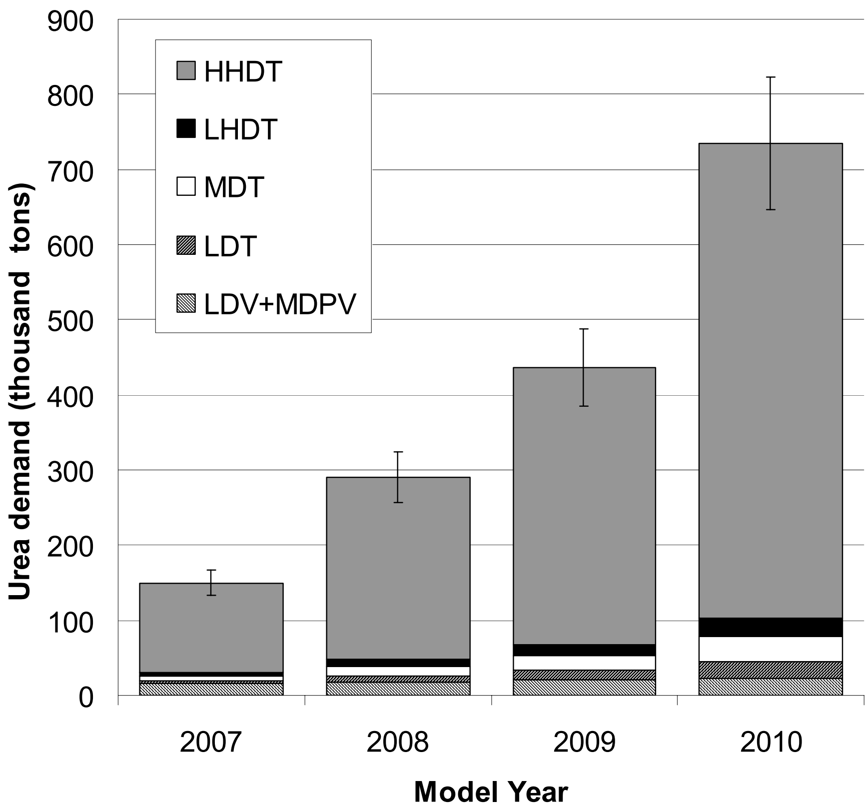


Figure 3-5. Projected Urea Demand from MY2007+ On-road Diesel Vehicles in the U.S. [41]

Urea Consumption from New Diesel Vehicles in Regions with a Large Vehicle Population

Regions in the United States with the largest vehicle population will require the majority of the on-road SCR-urea. ADL used state fuel tax records to determine what fraction of the nationwide diesel consumption was purchased in these regions (*i.e.,* California, Texas, and the Northeast), and assumed that this fraction would remain the same

[40] Miller, W.R., *et. al*., "The Development of Urea-SCR Technology," SAE 2000-01-0190.

[41] Taking the aforementioned assumptions as given (including the 18:1 diesel-to-urea consumption ratio), the cumulative estimation error is ±7%, where indicated.

through 2010. ADL also assumed that the distribution of diesel consumption and new vehicle sales among the vehicle classes is the same for both the regional and national levels through 2010. Using the fuel consumption and vehicle sales estimates, ADL projected the urea demand for California, Texas, and the Northeastern states combined (see Figure 3-6).

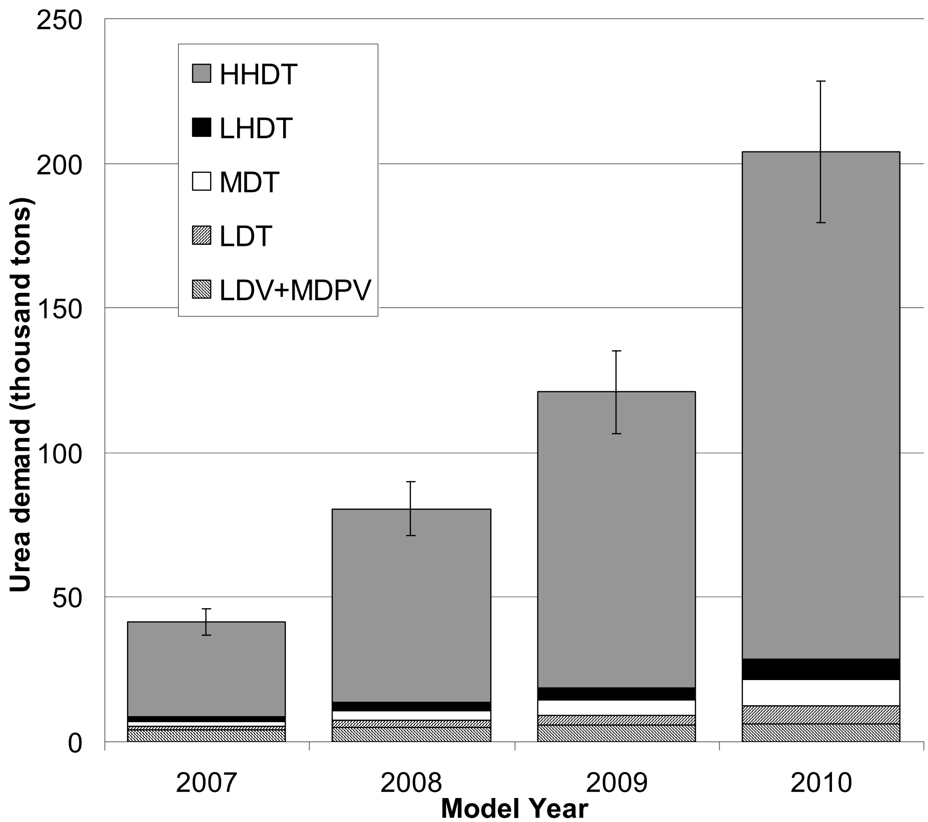


Figure 3-6. Projected Urea Demand from MY2007+ On-road Diesel Vehicles in CA, TX, and the Northeast U.S.

As an extreme case, ADL considered the possibility of these regions needing additional emissions reductions, and thus requiring SCR retrofits of existing diesel vehicles. If retrofits were required for all existing on-road diesel vehicles in certain areas, the SCR-urea demand would be more than five times the projected demand from new SCR-equipped vehicles alone. For example, Figure 3-7 shows the increased urea demand that would result from requiring SCR retrofits of all diesel vehicles in California, Texas, and the Northeast United States.

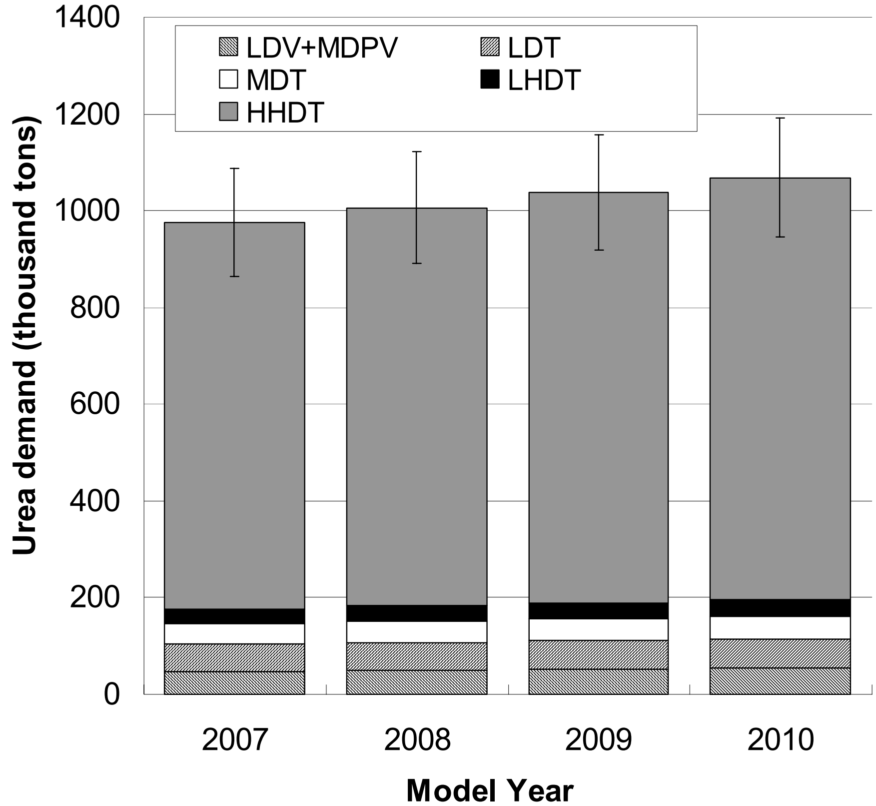


Figure 3-7. Urea Demand From On-road Diesel Vehicles in California, Texas, and the Northeast United States. Provided that All On-road Diesel Vehicles in those Regions are Sold or Retrofitted with SCR Systems

3.3 Projected United States Urea Consumption by Other Major Consumers

Projected Agricultural Consumption

Agricultural urea consumption is expected to remain relatively constant through 2010. Urea fertilizer consumption has remained steady for the past ten years, as domestic agricultural land use and crop production also has remained relatively stable. Developments in genetic engineering or other enhanced crop technology may eventually lead to a drop in fertilizer use. However, sector-wide adoption and acceptance of genetic engineered crops and related technologies has been gradual, and most crops are still developed from traditional sources. Thus, total fertilizer use is not expected to change significantly through 2010.

Projected Industrial Consumption

Industrial urea consumption rates are closely tied to the growth in the manufacturing sector of the U.S. economy. Thus, it may be assumed that industry urea consumption growth will track U.S. Gross Domestic Product (GDP) growth. As a result, industrial urea consumption is expected to grow in the long term, averaging about 3% annually, in step with the projected average GDP growth rate.

Future Stationary Urea Consumption

Another potential use of urea could be for SCR systems used in utility and other industrial fossil-fuel-fired systems. ADL estimated future stationary urea consumption from these sources. Under reasonably optimistic conditions of stationary SCR growth, it is expected that the increase in annual urea consumption will be less than 6 million tons per year by 2010.

ADL estimated the urea demand from stationary sources by first determining the stationary NO_x emissions nationwide for years 2001 and 2015. The stationary source NO_x emissions were determined by applying current and future EPA NO_x emission factors to the corresponding utility and industrial energy consumption data.[42] Based on current and projected trends, stationary power generation facilities will achieve 33% of their NO_x reduction from 2001 2015 levels by implementing SCR/SNCR (selective non-catalytic reduction).[43] Given the amount of NO_x reduction required, and assuming that the NO_x reduction will be achieved using urea (as opposed to ammonia or through another process), ADL applied a nitrogen stoichiometric ratio (NSR)[44] of 1.25 to determine the incremental amount of SCR-grade urea consumed by stationary sources.[45] Using this method, and assuming a linear urea demand growth between 2001 and 2015 for stationary power generation sources, ADL determined the incremental stationary urea demand for 2010 (see Table 3-7).

As shown in Table 3-8, the incremental urea demand for domestic stationary users is expected to be several times larger than the domestic on-road SCR demand.

[42] U.S. DOE Energy Information Administration, www.eia.doe.org.

[43] Instead of using a few centralized stacks, like those found at power generation sites, industrial facilities often use several small exhaust stacks. Using SCR/SNCR on multiple stacks increases the cost of using such technology per site, so SCR/SNCR was assumed to be used to reduce only 1% of industrial NO_x emissions.

[44] The nitrogen stoichiometric ratio is defined as the moles of nitrogen per mole of NO_x reduced.

[45] This conservative assumption that all future stationary SCR/SNCR systems will use urea is supported by a growing trend in the stationary power industry towards implementing urea-based SCR/SNCR when adding generation capacity.

Table 3-7. Incremental Stationary Urea Consumption for SCR/SNCR NO_x Control in 2010 (million tons)

NO_x Emissions Source	Additional Urea Consumed
Electricity generated	2.0
Industrial sources	3.4
Total	5.4

Table 3-8. Projected Domestic SCR-Urea Demand

Urea	Million Tons/Year
On-road, 2007	0.2
On-road 2010	0.7
Stationary[a], 2010	4-6 above current

[a]Stationary SCR-urea demand determined from domestic power generation data, power plant NO_x emission factors, and Federal NO_x emissions standards.

3.4 SCR-Urea Production and Demand Barriers and Solutions

Some uncertainties remain with regard to urea demand. As an extreme case, if all diesel vehicles were required to use SCR in 2010, then the urea demand would be more than five times higher, or 3.9 million tons (see Table 3-9).

Table 3-9. SCR-Urea Consumption in 2010 by On-road Diesel Vehicles under Moderate Market and Full Market (Extreme) Penetration Scenarios

	Million Tons Urea		
	HDV	LDV	Total
Moderate Scenario: All On-road Diesel Vehicles Compliant with MY2007+ Federal Emission Standards are Equipped with SCR Systems	0.66	0.08	0.74
Extreme Scenario: All On-road Diesel Vehicles (New and Existing) Equipped with SCR Systems	3.3	0.58	3.88

This is still within the excess capacity of the U.S. and world market, but it outstrips the U.S. excess production capacity when stationary SCR-urea demand is included. On-road SCR-urea demand remains uncertain beyond 2010, as it will depend upon the extent of diesel vehicle fleet penetration into the light- and heavy-duty vehicle markets, implementation of SCR compared to other NO_x control technologies, and changes in overall fuel consumption by all vehicle classes. Sections 3.4.1 and 3.4.2 address some additional SCR-urea production and demand barriers and solutions.

3.4.1 SCR-Urea Production Barriers and Solutions

Although there currently is an excess of urea manufacturing capacity available for increased urea production, as discussed in Section 2, it is not clear whether or not additional infrastructure investment is needed to meet the requirements of on-road SCR-urea. On-road SCR-urea is projected to increase domestic urea demand by about 7% in 2010. However, current domestic production is stable at 50% to 60% of rated capacity, and thus could be expanded to accommodate the projected on-road SCR demand. If necessary, there also exists sufficient excess production capacity worldwide to accommodate the on-road SCR demand in 2010.

3.4.2 SCR-Urea Demand Barriers and Solutions

Some issues remain to be resolved for meeting the on-road SCR-urea demand. The current urea production and distribution infrastructure mainly supports agricultural demand. Although total urea demand from agricultural and industrial sectors are expected to remain fairly steady, urea demand from the stationary sector is expected to grow, and may require an additional increase in domestic production capacity and/or imported urea to meet that demand. The stationary SCR-urea demand could potentially be met using infrastructure similar to that for the on-road SCR-urea. This may, in turn, encourage greater participation and/or competition among potential SCR-urea distributors, and thus possibly lower the distribution costs. Future diesel fuel consumption was estimated using a linear projection from recent historical values—future consumption may follow a non-linear trend resulting in greater actual SCR-urea demand.

High diesel penetration into the on-road light-duty market may lead to higher urea consumption. If all Tier 2 light-duty diesel vehicles employ SCR systems, a larger diesel vehicle penetration of the light-duty market could significantly increase the urea demand. Higher than expected diesel penetration may occur in the light-duty market if fuel economy standards are raised significantly. Additional urea demand estimates from the light-duty market for the 17% and 20% diesel penetration scenarios[46] are summarized in Table 3-10.

[46] EPA projects that light-duty diesel passenger vehicles and trucks would achieve a 2% and 17% light-duty market penetration, respectively, by 2010. "Regulatory Impact Analysis – Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements," EPA420-R-99-023, Table III.A-13, December 1999. DOE projects an average 20% light-duty market penetration by 2010 in a program impact report "Program Analysis Methodology: Office of Transportation Technology Quality Metrics 2002" DOE OTT. Tables A.9 and A.10.

Table 3-10. Estimated Additional On-Road SCR-Urea Demand in 2010 Due to High Market Penetration of New Light-Duty Diesel Passenger Vehicles and Trucks (million tons)

Light-duty Diesel Market Penetration	Additional Urea Demand in 2010	Total Projected Urea Demand in 2010
17% Diesel (Truck) Penetration	0.13	0.83
20% Diesel Penetration	0.15	0.85

Certain assumptions have been employed that may lead to an overestimated near-term urea demand. The urea demand projections presented in Table 3-8 assume all vehicles meeting Federal vehicle emission standards will use SCR. However, some vehicles subject to these standards may employ alternative NO_x-reducing technologies, reducing the SCR-urea demand. Also, urea consumption per gallon of diesel fuel is expected to drop with future generations of SCR systems as control technology improves,[47] thereby lowering anticipated urea demand.

[47] Miller, W.R., *et. al.*, "The Development of Urea-SCR Technology," SAE 2000-01-0190.

4. Selection of SCR-Urea Distribution, Storage, and Transportation Pathways

4.1 Background

Diesel is distributed to the end users in the transportation sector through a network of 1,350 bulk terminals. From the bulk terminals, diesel is then distributed to retail stations, which consist of about 4,750 truck stops, 55,300 service stations, and approximately 5,000 privately-owned fleet stations (not including fleet stations with 25 vehicles or less).

The approximate distribution of the potential SCR-urea end-user population is shown in Figure 4-1. Overall, a larger percentage of the diesel truck and bus population operates in fleets. However, a majority of the fleet population refuels at public stations (retail and truck stops) instead of fleet-owned fueling stations. Table 4-1 presents the fueling patterns of fleet trucks and buses in the United States. The fleet size distribution is presented in Table 4-2.

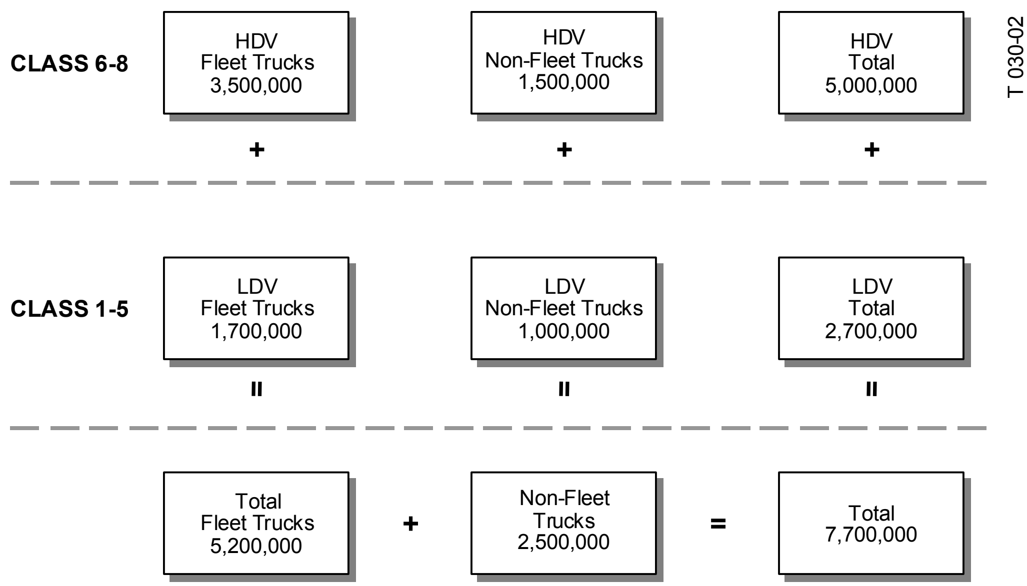


Figure 4-1. Diesel Supply Chain[48]

[48] ORNL, "Transportation Energy Data Book: Ed. 20," 2000; Automotive Fleet, Moilet Data, 2001; and Internal ADL estimates. Class 6-8 vehicles include Light-heavy-duty and Heavy-duty vehicles; Class 1-5 vehicles include light- and medium duty vehicles. Buses are included within these fleet population estimates.

Table 4-1. Distribution Fleet Trucks Refueling Characteristics[49]

	Distribution (%)
Fleet stations	30
Single-contract fueling facility	6
Public fueling stations	60
Other	4

Table 4-2. Fleet Characteristics[50]

Fleet Size	Vehicle Population	Number of Fleets
1,000+	1,065,000	360
500-999	654,000	1,485
100-499	672,000	4,310
25-99	214,000	7,715
Total	2,605,000	13,870

A system for urea distribution should parallel the diesel distribution infrastructure in most respects since the end-point for the SCR-urea is the same as that of diesel. ADL selected the existing infrastructures for agricultural-urea distribution and diesel distribution as a starting point for an analysis of the potential urea distribution infrastructure. The following subsections describe the key features that will be required in a urea distribution infrastructure. The benefits and barriers to using the current petroleum products infrastructure for SCR-urea distribution are summarized in Table 4-3.

The main elements of the SCR-urea infrastructure, as in the case of diesel, will include transportation, handling, storage, and dispensing. The quality of the SCR-urea required will be a key factor dictating the complexity of the SCR-urea infrastructure. For example, if the diesel engine manufacturers specify that passing industrial grade urea through the existing fertilizer-urea distribution channels will adequately maintain the quality of the urea, very little new infrastructure will be required for the transportation, storage and distribution (TS&D) of urea. However, if the SCR-urea has very low tolerances for contamination from the TS&D process, a complex and entirely new infrastructure will be required. To date, based on the information available (see Section 2), it appears that at least reagent grade urea with a low tolerance for cross-contamination will be required.

[49] ORNL "Transportation Energy Data Book: Ed. 20," 2000.

[50] Bobit Auto Group Research Dept. "Census of the U.S. Commercial Fleet & Non-Fleet Market." © 2000.

Table 4-3. Key Benefits and Barriers to Using the Existing Petroleum Products Infrastructure for SCR-Urea Distribution

Benefits	Barriers
1. Takes advantage of all aspects of an established diesel supply chain catering to the same end-users, e.g., transportation infrastructure, supply chain relations, etc. 2. Easier to integrate SCR-urea supply/demand relationship with the transportation diesel supply and demand, *i.e.*, a relatively reasonable learning curve. 3. Urea is a widely used commercial product and the general requirements for its transportation, storage, and handling are well established. It is also handled by many of the existing bulk terminal operators as an agricultural product.	1. Some form of a mandate may be required to energize the various participants along the supply chain. The mandate may have to come with benefits and subsidies for implementation. 2. Participants will be reluctant to invest initial capital involved with transportation, handling, storage, and distribution. 3. Participants may be reluctant to invest in other new costs incurred from training for handling of urea, QA/QC along the supply chain, environmental liability, operating costs, etc.

Based on preliminary information, it appears that SCR-urea developmental work is leaning toward co-fueling (*i.e.*, dispensing diesel and urea simultaneously). Therefore, a key assumption made in this report is that SCR-urea will be co-fueled. The distribution pathways discussed in the next section are based on this assumption. If a different technical approach for SCR-urea implementation is followed—such as a distribution infrastructure similar to that of lube-oil or coolant—then a different distribution infrastructure will evolve.

4.2 Distribution Pathways

Under the vehicle penetration scenario described in Section 3, about 0.7 million tons of urea may be required as on-road SCR-urea by 2010. However, if all new and existing diesel vehicles were to implement SCR systems, almost 4 million-tons of urea would be required (see Table 3-9). Sufficient domestic rated production capacity exists to handle an increase in urea demand of this magnitude. However, whether or not mobile SCR urea demand is met by domestic manufacturers depends upon the price of natural gas—since natural gas is the principal feedstock for urea—as well as the quality of urea needed (Section 2).[51] A highly competitive, low-cost, foreign-urea market is also available.

[51] As previously mentioned, domestic stationary SCR/SNCR urea demand is expected to increase in the next decade and thus is expected to provide additional domestic demand for urea.

Key factors that will affect the choice of an SCR-urea distribution pathway include:

- Quality of urea
- Source of urea
- Tolerance for contamination from TS&D process
- Solid or aqueous urea for distribution from the plant to the terminal
- Distances between various points in the supply chain
- Available modes of transportation

ADL determined a set of nine major SCR-urea distribution pathways based on the above factors. These nine pathways, along with key steps in the distribution process, are presented in Table 4-4. The table also broadly categorizes feedstock urea supply sources into domestic sources and foreign sources. While it is possible that a number of other pathways for distribution will develop, they will most likely fall into the framework of the matrix generated in Table 4-4. Figure 4-2 shows an example of one of the major pathways. Appendix B provides a graphical representation for all nine pathways.

The following subsection describes the key characteristics that will evolve and/or be required for the transportation, handling, storage, and distribution of SCR-urea. However, before addressing these issues, purity and cross-contamination must be addressed.

Table 4-4. SCR-Urea Distribution Pathways

Pathway	Imported Urea			Domestically Manufactured Urea					
	1	2	3	4	5	6	7	8	9
Granular (G) or Aqueous (A) Urea	G	G	G	G	G	G	A	A	A
Shipping and Unloading	X	X	X						
Transport to Plant and Storage	X	X							
Bagging and/or Bulk Loading	X								
Blending at Plant		X			X	X	X		
Loading at Plant		X		X	X	X	X		
Transport from Plant to Terminal, Unloading, and Storage	X	X	X	X	X			X	
Blending at Terminal	X		X	X				X	
Loading	X	X	X	X	X			X	
Transport to Retail Facility, Unloading, and Storage	X	X	X	X	X	X	X	X	X
Blending at Retail Facility									X
Dispensing	X	X	X	X	X	X	X	X	X

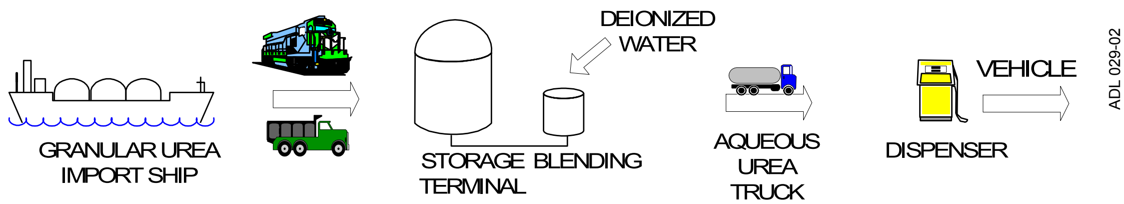


Figure 4-2. Pathway #1: Imported Urea Blended at Storage Terminal and Trucked to Retail Distributor

4.2.1 Urea Purity and Cross-contamination Issues

As noted previously, a specification for the required SCR-urea purity has not been established. However, if high purity urea is required, the supply chain will be affected at various levels. Table 4-5 compares the key effects of urea purity on the distribution components. In general, if the SCR system will not tolerate any urea cross-contamination between urea grades, then a mostly new, dedicated infrastructure will be required. If contamination tolerances can be relaxed, stringent infrastructure requirements will ease and portions of the existing urea infrastructure can be utilized to transport, store, and distribute SCR-urea.

Table 4-5. Effect of Urea Purity on Distribution

Purity of Urea	High	Medium	Low
Tolerance for Contamination	Zero	Low	Moderate
Equipment	• Dedicated • New • Special material lining/coating will be required, e.g., fluoropolymer linings	• Dedicated • Some existing equipment may be used • No special materials	• Cross-use existing agricultural/industria l equipment for urea • No new equipment • No special materials
Transport of granular urea	• Dedicated, lined-containers for bulk (or) • Specially lined bags/totes for bagged urea	• Dedicated, existing containers	• Cross-use containers
Transport aqueous urea	• Dedicated, specially lined containers	• Dedicated, existing stainless containers	• Existing containers for ag/industrial use
Storage, handling, and transfer	• Dedicated, specially lined equipment • Rigorous QA/QC procedures at all transfer and storage points	• Dedicated, existing equipment • Rigorous QA/QC procedures at all transfer and storage points	• Cross-use • Moderate QA/QC procedures
Relative cost of TS&D infrastructure	High	Moderate	Low

4.2.2 Transfer and Handling

Urea transfer at various points in the distribution chain will occur at the plant, at the ports, at the bulk terminals, and at the retail stations. The purity and tolerance for contamination will dictate the mode of loading, unloading, and transferring urea. When cross-contamination is not a critical issue, typical mechanical methods such as screw feeders, conveyors, and bulk loaders will be used. Where cross-contamination will compromise SCR-urea effectiveness, specially-lined (with a fluoropolymer material—Teflon© as an extreme example) pneumatic equipment or similar equipment, will be required. Transferring the high-purity aqueous urea will require specially lined pumps and piping.

4.2.3 Transportation

Transportation of granular urea from foreign sources will occur primarily by ship. Domestic transportation of the SCR-urea will mostly occur by rail and truck. Some of the key assumptions about transporting the SCR-urea are summarized in Table 4-6 below.

Table 4-6. Urea Transportation Assumptions[52]

Mode	Ship	Truck Port to Terminal	Rail Port to Terminal	Truck Terminal to Retail
Solid SCR-Urea (tons/year)	1,000,000	500,000	500,000	1,000,000
Average distance, (miles)	7,500	200	750	100
Average size of shipment (tons)	25,000	25	600	25

As noted previously, the containers will have to be specially lined to avoid contamination from corrosion/erosion of the walls and fittings when high purity urea is required. When such corrosion issues and other cross-contamination issues are not significant, the existing container types and containers could be used to various degrees.

If the high-purity solid urea is transported in specially lined bags or totes that can be loaded into existing containers, some of the new container requirements will be eliminated on the solid-urea transport side. The purity requirements will also dictate whether new lined tankers will be required for aqueous SCR-urea transport.

[52] See Appendix C table "Transportation Assumptions" for details of estimate.

4.2.4 Storage

Once again, the degree of tolerance for SCR-urea contamination along TS&D pathways will dictate the types of storage containers used. Table 4-7 summarizes the various features of the storage requirements.

Table 4-7. Key Characteristics of Storage Infrastructure[53]

	Plant	Bulk Terminal		Retail	
				Truck Stop	Service Station
SCR-urea form	Solid urea	Solid Liquid: (70% by weight)		Liquid (32.5% by weight)	Liquid (32.5% by weight)
Capacity per location	—	Solid: 25-50 tons Liquid: 7,500-15,000 gal		7,500 gal	500 gal
Location	—	Solid: above ground Liquid: underground		Underground	Underground
<u>Storage requirements</u>		Solid	Liquid (70% by weight)	Liquid (32.5% by weight)	Liquid (32.5% by weight)
High purity	—	New	New	New	New
Medium purity	—	New	New	New	New
Low purity	—	Existing	New	New	New

An important factor affecting the storage of liquid urea is its temperature. Aqueous SCR-urea (32.2 wt% urea) will salt-out at around –11°C. This temperature is not low enough to prevent crystallization during the cold months in many parts of the United States. Therefore, the SCR-urea tanks may require heating in addition to underground storage.

4.2.5 Blending

Both solid urea and urea liquor (70% urea by weight) will have to be blended with de-ionized (DI) water in order to minimize additional urea contamination. The most economic source of DI water will be onsite production. Therefore, DI water systems will have to be installed at the terminal level for most distribution pathways. In some cases, when blending occurs at the service station level, DI water will have to be produced onsite at the service station. The level of de-ionization will depend on the purity requirements. A typical DI system will consist of reverse osmosis (RO) membranes followed by polishing with ion-exchange media.

[53] See Appendix C, table “Transportation Assumption” for details; and see Appendix E table “Storage Cost” for details.

4.2.6 Dispensing

An "average" truck stop has five diesel pumps.[54] An average service station has one diesel pump. Assuming a portion of service stations will provide SCR-urea dispensers by 2010, and all will in the future, Table 4-8 summarizes the urea refueling requirements.

Table 4-8. Urea Dispensing Requirements

	Truck Stops	Service Stations	Fleet Stations
Number of refueling stations	5,000	55,000	5,000
Diesel islands per station	5	1	5

Strategies and technologies for dispensing urea to the end-user at the retail level are still evolving. As noted previously, one proposed strategy is co-fueling of diesel and urea. This strategy is being developed by Ford Motor Company.[55] In any case, completely new infrastructure for dispensing the SCR-urea will be required. Key elements of the dispensing infrastructure will include: metering systems, storage/pumping systems, and co-fueling or other nozzles.

4.3 Training and Other Requirements

In order to ensure an effective and efficient production and distribution system, a quality assurance and control (QA/QC) program must be in place. The extent of the QA/QC program will depend on the tolerance for contamination.

The QA/QC procedures may include special handling and storage procedures. Sampling and testing along the distribution chain to verify urea composition may have to be implemented. Urea certification programs may also be required. These requirements will require new training at all levels — from plant inspectors to urea handlers.

Another component of the infrastructure is the establishment of environmental and health and safety procedures. Although urea is not listed by EPA or DOT as a hazardous compound, due to the large-scale storage and transportation requirements existing emergency and standard response procedures at the various points in the supply chain will have to be updated to include urea. This may also involve additional training requirements. This topic is further discussed in Section 6.

[54] Herzog, Jeff, "Memorandum to Air Docket A-99-06." EPA, OTAQ, Ann Arbor, MI, March 2000.

[55] ADL communications with Dick Baker "Diesel Cross-Cut Team," May 2002.

5. Urea Production and Distribution Life-Cycle Cost

As presented in Section 4, the main components of the SCR-urea distribution infrastructure are:

- Transportation
- Storage/blending
- Dispensing
- Training

The key assumptions for each component are presented in summary tables in Section 4. Figure 5-1 presents the various cost elements considered for each component. Appendices C and D present in detail the assumptions and calculations made in developing the cost estimates.

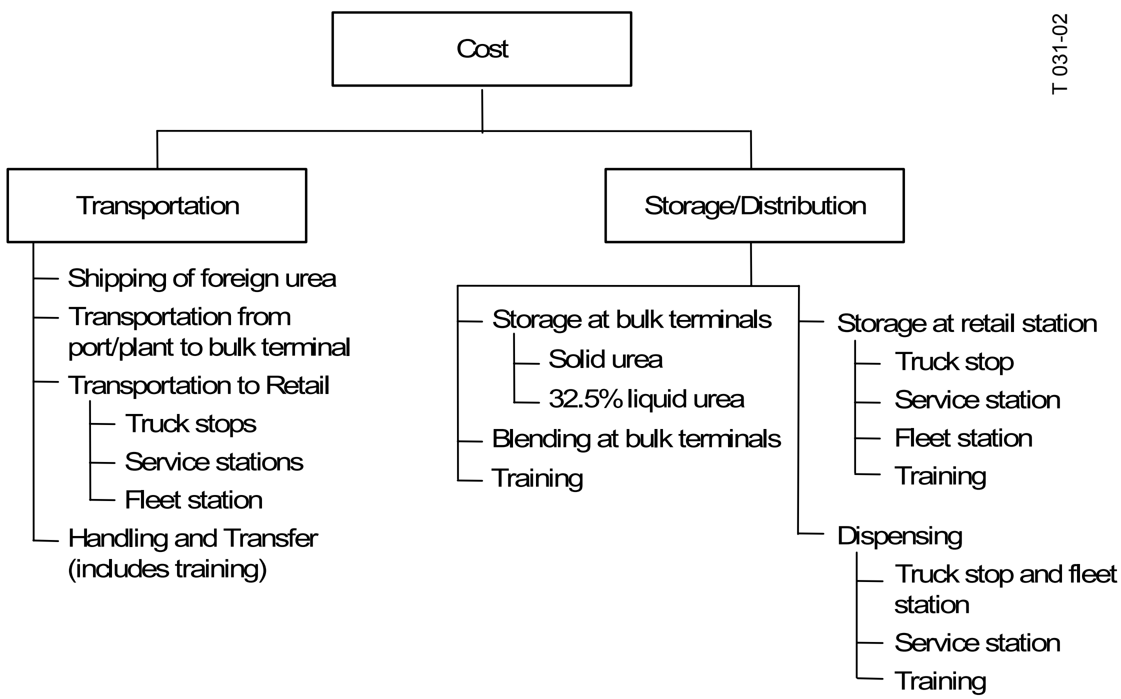


Figure 5-1. Elements of an SCR-Urea Distribution Infrastructure Cost Analysis

The cost estimates were divided into two major categories. The first cost estimate category was based on the quantity of urea consumed, with the lower and upper bounds of future urea consumption estimated to be between 0.7 and 3.9 million tons/year, respectively (see Section 3.4, Table 3-9).[56] The second cost estimate category was

[56] For simplicity in the following analysis and discussion, ADL assumed that the cost estimates are bounded by an annual consumption of 1 to 4 million tons.

based on the purity of the urea, assuming high purity SCR-urea with zero tolerance for contamination. These two sets of assumptions set the boundaries for the cost estimates.

Finally, the entire supply-chain cost for Pathway 1 (see Section 4.2) was estimated for five different cases. These five cases encompass the most plausible range of costs.

5.1 Transportation Costs

5.1.1 Shipping of Foreign Urea

Foreign urea will be shipped mainly from ports in the Arabian Gulf States, former Soviet Union countries, and Venezuela. In the case of high purity urea, anew infrastructure will be required to protect SCR-urea from contamination. The cost of the new infrastructure is estimated to be between $75 to $77 per ton of urea and domestic importers are most likely to see this cost rolled into the freight-on-board (*i.e.*, dockside) price of the imported urea.

The cost estimate includes a handling and transfer charge of $4/ton. This is a nominal charge for handling bulk goods at ports and other transfer points. Another component of the shipping cost is the equipment required to transport high purity urea with no tolerance for contamination. A charge of $8-10/ton was used for the special bulk-container/bag/tote requirement. Details of the shipping cost assumptions and calculations are presented in Appendices C and D. Table 5-1 presents a summary of the foreign urea shipping costs.

Table 5-1. Foreign Urea Shipping Costs

Urea Purity	High	Low
Bulk ($/ton)	75	67
Bagged ($/ton)	77	67

Assumptions:
1. Annual urea shipments: 1-4 million tons
2. Average distance shipped one-way
3. Handling charges: $4/ton
4. Special container charges: $10/ton (bagged), $8/ton (bulk)
5. Costs include training and other overheads
6. Capital investment recovered over 3 years, assuming a 10% interest rate

5.1.2 Transportation from Port to Bulk Distribution Terminal

Transportation of urea from the port of entry to the bulk terminals will primarily occur by rail and truck. There are 1,350 bulk terminals distributing petroleum and fertilizer products. These terminals are distributed over 350 geographic locations. Diesel is also mainly distributed through these terminals to the retail end-users. ADL assumed that nearly 650 terminals (about 50%) will be involved in the distribution of urea. This ensures an adequate regional distribution that parallels the diesel distribution infrastructure. The shipment of urea from the port to the terminal is assumed to occur both by rail and road. Further details on the assumptions and cost calculations may be found in Appendix D, table “Transportation Costs.” Table 5-2 summarizes the assumed transportation costs.

Table 5-2. Transportation Cost to Bulk Terminals

Annual Urea Shipments	1 Million Tons per Year		4 Million Tons per Year	
Urea Purity	High	Low	High	Low
Bulk ($/ton)				
Train	51	51	51	23
Truck	29	22	29	22
Bagged ($/ton)				
Train	23	23	23	23
Truck	22	22	22	22

Assumption:
1. Urea transportation distributed evenly between rail and road.
2. Costs include training and other overheads.
3. Capital investment recovered over 3 years, assuming a 10% interest rate.

5.1.3 Transportation of SCR-Urea Solution (32.5% by weight) from Terminal to Retail Station

Transportation to the retail station from the bulk terminals will occur in typical 8,000-gallon capacity tanker trucks. The type of the container will depend on the purity of the urea. The 650 or so bulk storage terminals will supply the SCR-urea to a network of 4,750 truck stops, 5,000 fleet stations, and 55,300 service stations. Table 5-3 presents a summary of the transportation costs. Details of the assumptions made and the calculations are shown in the Appendix D table “Urea Transportation Costs.”

Table 5-3. Transportation Cost to Retail Stations

Urea Usage	1 Million Tons per Year		4 Million Tons per Year	
Urea Purity	**High**	**Low**	**High**	**Low**
Truck stop (& fleet station)	25	15	17	15
Service stations	43	33	35	33

Assumptions:
1. Average trip to truck stops (and fleet station) is 100 miles. One truck stop delivery per trip.
2. Average trip to service stations is 200 miles. Up to 10 service stations per trip.
3. 7,500 gallon of SCR-urea per trip (nominally 12 tons of solid urea).
4. Costs include training and other overheads.
5. Capital investment recovered over 3 years, assuming a 10% interest rate.

5.2 Storage and Blending at Bulk Terminals

Granular urea brought in from the ports and plants will be stored onsite at the terminals in hoppers before being processed further. Further processing will involve blending with SCR-urea and storage until distribution. The storage and blending costs are summarized in Table 5-4. Details of the cost assumptions and calculations are presented in Appendix D tables "S&D Costs." The blending costs are included in the storage cost of the 32.5% by weight SCR-urea solution.

Table 5-4. Storage and Blending Costs

Urea Usage	1 Million Tons per Year		4 Million Tons per Year	
Urea Purity	**High**	**Low**	**High**	**Low**
Storage and blending costs ($/ton)	87	61	22	16

Assumptions:
1. Costs include storage of solid and liquid urea at the bulk terminal.
2. Urea usage evenly distributed between 650 bulk terminals.
3. Costs include training and other overheads.
4. Costs include DI water infrastructure.
5. Equipment investment recovered over 3 years, assuming a 10% interest rate.

5.3 Storage and Dispensing at Retail Location

The SCR-urea will be stored in 500-gallon capacity underground storage tanks. Special dispensing equipment will be required. The infrastructure elements included in the cost analysis were summarized in Section 4. The costs of storage and dispensing are summarized in Table 5-5 below. Details of the cost assumptions and calculations are presented in the Appendix D table "S&D Costs."

Table 5-5. Storage and Dispensing Costs — Retail Station

Urea Usage	1 Million Tons per Year		4 Million Tons per Year	
Urea Purity	**High**	**Low**	**High**	**Low**
Costs ($/ton)				
Truck stop (& fleet station)	1,740	1,700	451	424
Service stations	23,600	22,300	3,110	2,930

Assumptions:
1. Costs include storage and dispensing costs.
2. All retail stations are expected to install dispensing infrastructure.
3. Assumes all truck stop (5,000), fleet stations (5,000), and service stations (55,000).
4. Capital investment recovered over 3 years, assuming a 10% interest rate.

5.4 Urea Distribution Chain — Costs for Five Cases

Five cases combining various levels of urea purity and form (bulk vs. bagged) were selected to estimate the total cost of urea TS&D. Costs A through C are variations of Pathway 1. Cases D and E are based on Pathway 4. Table 5-6 presents a summary of the five cases. These cases represent an envelope of costs. It is reasonable to expect that the eventual TS&D of a majority of the SCR-urea will be some combination of these five cases.

Table 5-6. Characteristics of Five Distribution Scenarios

	Case				
	A	**B**	**C**	**D**	**E**
Foreign shipment	Yes	Yes	Yes	No	No
Urea purity	High	High	Low	High	Low
Bulk loads	Yes	No	Yes	Yes	Yes
Bagged loads	No	Yes	No	No	No
	$/ton				
Foreign shipment	75	77	67	—	—
Transportation to terminal	40	23	23	40	23
Storage and blending; terminal	87	87	61	87	61
Transportation to retail station					
Truck stop (and fleet station), or	25	25	17	25	17
Service station	43	43	35	43	35
Storage and dispensing; retail station					
Truck stop (and fleet station), or	1,739	1,739	1,704	1,739	1,704
Service station	23,631	23,631	22,287	23,631	22,287

Assumption:
1. 1,000,000 tons of urea usage annually.

Table 5-6 also presents the costs of the various components of the TS&D chain for each of the 5 cases, assuming an annual SCR-urea consumption of 1 million tons.

The total and fractional costs for the five cases are graphically represented in Figures 5-2 through 5-5 on a $/ton of solid urea and $/gal of SCR-urea solution basis. A key conclusion is that the majority of the urea TS&D infrastructure cost is due to capital investments at the retail station levels. The capitalized costs at the retail station level are a function of the quantity of urea dispensed at the stations. Therefore, as assumed here, if every diesel retail station is expected to have SCR-urea dispensing infrastructure, then the costs may become prohibitive. The costs will decrease with increasing quantities of urea dispensed at the retail stations. As the urea consumption is limited by the number of vehicles with SCR systems, economies of scale will dictate that not all retail stations will dispense urea.

As mentioned in Section 3, further developments in technology may reduce the amount of urea required per gallon of diesel consumed. As a result, instead of a complex infrastructure at the retail level, perhaps only bottled urea storage may be required for light-duty vehicles — similar to engine lubricant storage. If such a system evolves, it will be necessary to evaluate new costs, such as bottling, incurred along the supply chain.

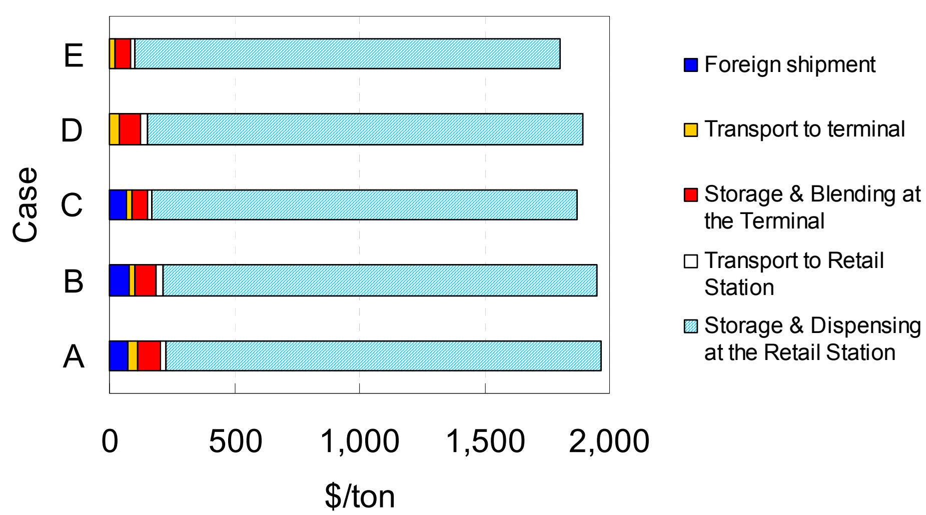


Figure 5-2. SCR-urea Distribution to Truck Stops and Fleet Station Costs

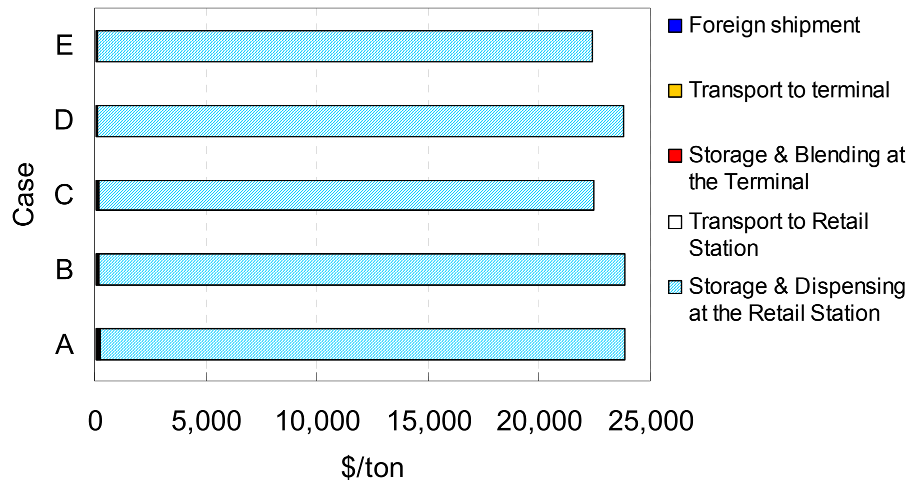


Figure 5-3. SCR-urea Distribution to Service Station Costs

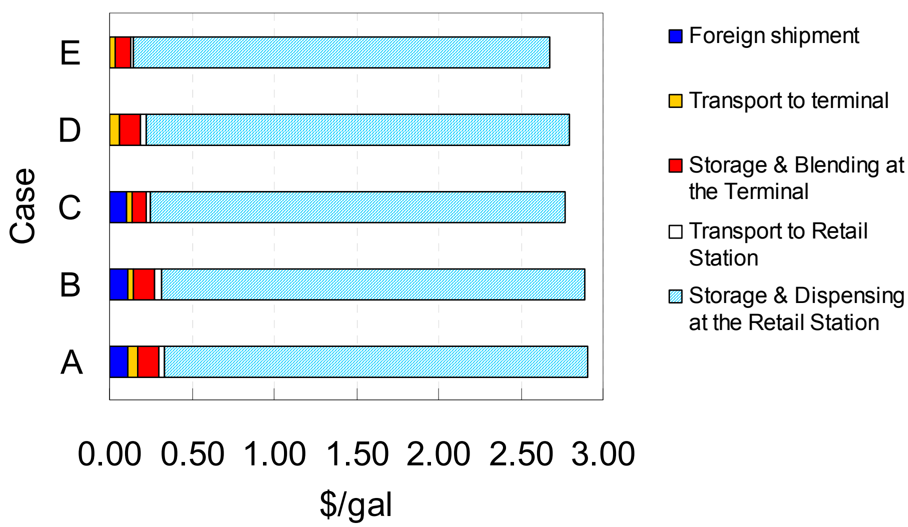


Figure 5-4. SCR-urea Distribution to Truck Stops and Fleet Station Costs

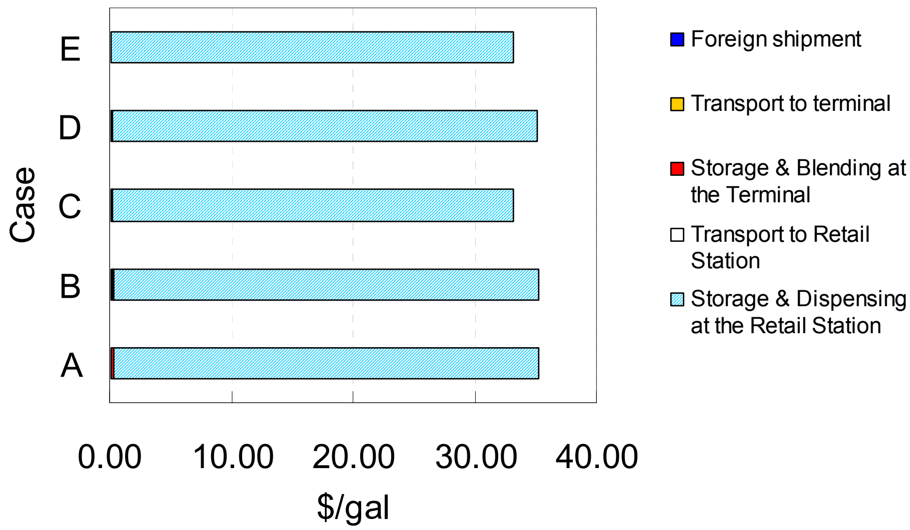


Figure 5-5. SCR-urea Distribution to Service Station Costs

5.5 Urea Production Cost

Almost all urea plants in the world are located in conjunction with an ammonia plant, as ammonia is the feedstock for urea. The feedstock for the industrial production of ammonia is natural gas. Therefore, it is not surprising that the cost of urea closely tracks the cost of natural gas. Figure 5-6 shows the cost of urea manufacture as a function of the price of natural gas. Most of the urea traded in the world markets is agricultural urea. The basket price of urea closely tracks the price of natural gas, and in the last 3 years has fluctuated between $80/ton to $200/ton.

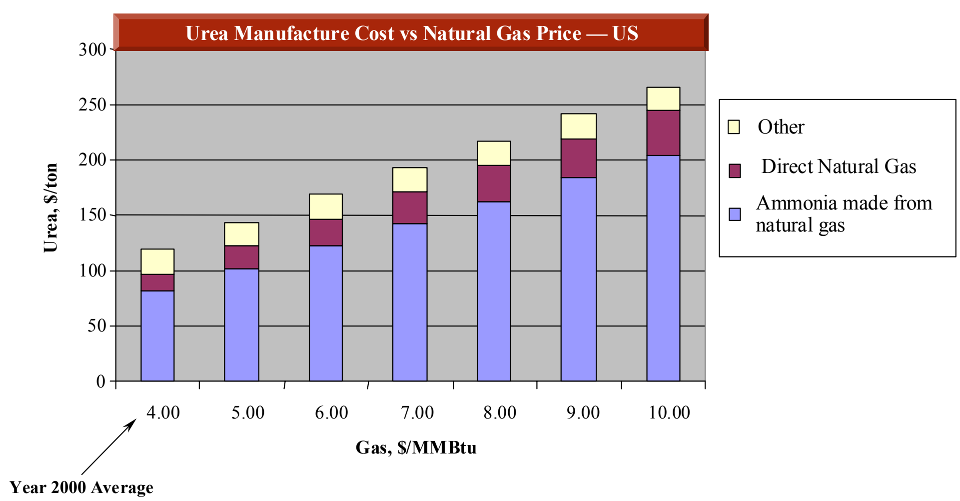


Figure 5-6. Urea Manufacturing Cost Versus Natural Gas Prices

The demand for SCR-urea can be expected to be stable and non-seasonal, thereby removing price instabilities seen by agricultural urea. Since the eventual composition and quality of the SCR-urea is unclear at this time, it is assumed that solid SCR-urea cost of production will also range between $80 to $200 per ton.

5.6 Final Retail Cost of Urea

The retail cost of urea at the pump will include the cost of production, cost of distribution, and other profit mark-ups along the supply chain. Table 5-7 below presents the potential range of costs based on an annual usage rate of 1 to 4 million tons/year for the selected pathways.

As noted in earlier sections, the pathways selected for this study are representative of most distribution channels that would evolve under the current assumptions of the infrastructure, such that the dispensing stations and bulk terminals would parallel the existing diesel infrastructure. The costs presented in Table 5-7 also represent a range of costs that envelop these potential pathways.

Table 5-7. Retail Cost of Urea

SCR-Urea Costs	$/ton	$/gal
Production	80 to 200	0.12 to 0.30
Distribution	500 to 24,000	0.70 to 35
Dealer mark-up along the supply chain	—	0.05 to 0.10

Assumptions:
1. Assume annual SCR-urea usage rate of 1 to 4 million tons.
2 650 bulk terminals, 5,000 truck stops, 55,300 service stations, and 5,000 fleet stations.
3. Mark-up adapted from diesel supply chain costs.

6. Environmental Impact of Urea Use

As discussed in the previous section, a portion of the on-road SCR-urea TS&D infrastructure will utilize existing urea distribution pathways. Operators that transport SCR-urea along pre-existing segments of the SCR-urea TS&D infrastructure would not require additional training or preparation to handle potential urea spills. Those pathway segments that will be created under the development of an SCR-urea infrastructure will need to develop precautions that minimize the environmental impact of spills. Such precautions would be developed by proper consideration of the issues discussed in this section.

6.1 Preliminary Impact of Urea Spills

The potential impact of urea spills along the TS&D infrastructure – from production site to retail station – is discussed in the following subsections. Although not discussed here, urea and urea-related emissions and spills from vehicles may also warrant consideration and further study in future reports.

6.1.1 Potential Sizes of Spills

The largest spill potential exists when importing solid urea. The largest cargo vessels used to ship solid urea have a total capacity of 44,000 tons (40,000 metric tons). Thus, if an import shipment comprised solely of solid urea capsized, then the largest spill would be 44,000 tons in the ocean and/or coastal and harbor waters. Land transport and transfer modes involve much smaller amounts of urea. Federal regulations limit train length to about 90 cars, with each railroad hopper car holding up to 106 tons (96 metric tons) urea, so the maximum spill from a train carrying solid urea – unlikely, but still possible – would be about 9,500 tons (8,600 metric tons).

These potential spill volumes depend on the individual transportation container capacity for urea transport pathways already in existence. An SCR-urea infrastructure would channel urea imports through these existing pathways, and thus the potential spill volume for these pathway segments would be the same as under the current urea distribution infrastructure.

Unlike the import and railcar pathway segments, the urea blending, storage, and transportation to retail stations pathway segments are unique to an SCR-urea infrastructure. Spills along these segments represent a new potential environmental impact, and thus require special attention. Potential spill volumes for urea solution distribution containers reach up to 7,800 gallons of urea solution—the typical transport container capacity. Potential spills at blending sites include transfer spills—which could be as large as a typical transport container capacity—and spills from storage tanks that hold as much as 50,000 gallons. For a table describing the anticipated spill volume along all segments of the previously described pathways, see Appendix E.

Preliminary Internet searches for past urea spills along transportation pathways revealed few references to specific spills. One specific reference involved a spill from the barge *Oregon* that capsized in January 1997 near Ninilchik, Alaska and spilled its urea cargo totaling 12,500 tons.[57, 58] Among the cases found in a preliminary search, the response actions included contacting the U.S. Coast Guard (for spills involving waterways) as well as state and local health and environmental agencies.

The proper SCR-urea spill response measures will depend upon whether or not the material is considered hazardous. Table 6-1 shows which federal agencies consider urea to be hazardous and/or carcinogenic.

Table 6-1. Listing of Urea as Hazardous and/or Carcinogenic by Federal Agency[59]

Agency Listing	Hazardous	Not Hazardous	Carcinogenic	Not Carcinogenic
EPA		X		X
OSHA	X[a]			X
DOT		X		
Federal Hazardous Waste Regulations (40 CFR 261)		X		

[a] Some of the manufacturers' MSDS surveyed for this report indicate that urea is not hazardous under OSHA Hazard Communication Standard (22 CFR 1910.1000).

Appropriate local and state contacts for spill response of chemical materials should be determined in advance for each of the new urea SCR distribution pathways. As an additional resource, the U.S. Coast Guard currently maintains a National Response Center hotline for reporting hazardous material spills that will assist in notifying the appropriate agencies in an emergency.[60]

In order to determine the likelihood of urea spills within an on-road SCR-urea infrastructure, further study of past urea spills and spills of other chemical products transported along similar pathways is recommended.

6.1.2 Clean-up Options

Limited information exists with respect to urea cleanup beyond that of small spills of solid granular product. Urea manufacturers' material safety data sheets (MSDSs) note that minor spills—those involving "a single, small package (up to a 55 gallon drum),

[57] Alaska Department of Environmental Conservation, "Quarterly Provisional Data Release: Oil and Hazardous Substance Releases." March 31, 1997.

[58] Unocal Corporation, "1996-97 Health, Environment, and Safety Report: Communicating Risk and Responding to Emergencies." www.unocal.com/responsibility/96hesrpt/barge.htm. Accessed May 10, 2002.

[59] CF Industries, "MSDS for urea Solid." April 17, 2000; Cargill Fertilizer Inc., "MSDS for Urea Liquor."

[60] United State Coast Guard National Response Center. Open 24 hours, 7 days a week at 1-800-424-8802. www.nrec.uscg.mil. Accessed May 2002.

small cylinder or a small (non-continuing) leak from a large container"[61]—do not normally require any special cleanup measures. The MSDSs also indicate that in the event of major spills, urea should be prevented from entering drains and watercourses. If the product has gained moisture, an absorbent material such as sand may aid in recovery. Sweeping and shoveling the spilled product into labeled containers for recycling or salvage is recommended. The affected area should be cleaned to prevent runoff from entering drains. Recovered product is considered non-hazardous waste by EPA and the Resource Conservation and Recovery Act and may be used as fertilizer or disposed of as necessary. If disposal of contaminated materials is necessary, the materials should be placed in disposable containers and disposed of in a manner consistent with applicable local, state, and federal regulations.[62]

6.1.3 Potential Soil, Air, and Water Impacts

6.1.3.1 Urea Reactions/Impacts in Soil

Based upon urea's application as an agricultural fertilizer, its behavior when applied to soil in a solid form is well documented. Available information indicates that when urea is released to soil, it will hydrolyze into ammonia over a period of days to weeks.[63] Equation 6-1 presents the chemical reaction forming ammonia and carbon dioxide from urea and water.

$$CO(NH_2)_2 + H_2O \rightarrow CO_2 + 2NH_3 \tag{6-1}$$

According to Overdahl, *et. al.*, urea breakdown begins immediately upon application to soil. No reaction will occur if the solid is completely dry. However, with the enzyme urease, plus any small amount of soil moisture, urea normally hydrolyzes to ammonia and carbon dioxide. This can occur in two to four days, and will occur faster in soils exhibiting high pH. When urea dissolves, the surrounding area becomes a zone of high pH and ammonia concentration. This zone can be fairly toxic to plant life during this period. Usually within a few days, ammonia converts to ammonium and this toxic zone is neutralized, and plants can effectively use the nitrogen. Chemical conversion generally continues as ammonium is converted to nitrate. Equation 6-2 presents this reaction.

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \tag{6-2}$$

It is clear from the chemical progression discussed above that urea released to soils will eventually be converted to nitrate.

[61] Terra Nitrogen Corporation, "Material Safety Data Sheet Number 2046 for Urea Liquor." January 14, 2002.

[62] Terra Nitrogen, Corporation "MSDS for Urea;" CF Industries, Inc. "MSDS for Urea." April 17, 2000; Cargill Fertilizer, Inc., "MSDS for Urea." May 2000.

[63] Overdahl, *et. al.*, www.extension.umn.edu/distribution/cropsystems/DC0636.html. Accessed November 2001.

6.1.3.2 Urea Reactions/Impacts in Water

Depending on local geology, soil conditions, and topographical factors, nitrate may be transported down to the local water table and impact groundwater. There is also a potential for nitrate migration to surface water. As discussed in the previous section, urea reacts rapidly with water to form ammonia, and subsequently ammonium, which then undergoes bacterially-mediated oxidation to form nitrate.

Nitrate is regulated under EPA's primary drinking water standards. The drinking water standard for nitrate (measured as total nitrogen) is 10 mg/L. Consuming drinking water with elevated concentrations of nitrate can cause a blood disorder in infants known as methemoglobinemia.

6.1.3.3 Urea Reactions/Impacts in Air

When urea particles are released into the air, the urea is expected to undergo rapid degradation into carbon dioxide and ammonia by reaction with photochemically produced hydroxyl radicals. It is estimated that when released into the air, urea will have a half-life of less than one day. The resulting ammonia may then form secondary particulate matter, thus impacting local air quality. Previous studies have looked at the health effects of ammonia and particular matter concentrations in ambient air, but not at the impact of urea concentrations. The magnitude of air quality and health impacts from airborne urea are not clear at this time and require further study.

6.1.3.4 Urea Ecotoxicity

As mentioned above, urea will slowly convert to ammonia and eventually degrade to nitrate. Although ammonia is a toxic hazard to fish, it is noted that ammonia release from urea is slow, indicating urea is less toxic than ammonium salts. Aquatic toxicity tests indicate that 24-hour exposure at 16,000 mg/L of urea was not fatal to Creek Chubs. Urea ingestion may be toxic to mammals and birds at high body burdens (several thousands of mg/kg).

Urea can be toxic to domestic animals and has caused poisonings when it was applied unevenly on pastures as a fertilizer. At high concentrations, urea can be toxic to aquatic life and foster excessive growth of algae or microorganisms in water systems.[64]

6.2 Estimated Human Exposure Effects

When handled under "normal conditions of careful, responsible use," urea poses a low health risk to humans that handle urea in large quantities—such as at a terminal transfer point—and poses a very small risk to those that interact with it in small quantities—such

[64] CF Industries, "MSDS: Urea." 2000.

as dispensing at the retail station.[65] However, overexposure to urea can cause irritation, erythema, nausea, vomiting, and increased urination in humans.[66] The Industrial Resources Group urea MSDS provides the following guidelines for contact with urea.

6.2.2.1 Direct Ingestion

If urea is ingested, rinse mouth and drink plenty of water. Induce vomiting if exposed to high volumes of a low concentration. Obtain medical attention in all cases.

6.2.2.2 Transdermic Absorption

If urea comes in contact with skin, wash affected areas with soap and water. Urea is slightly corrosive in water and is a mild irritant. If urea gets in the eyes, flush with large amounts of water for a minimum of 15 minutes. May cause irritation, redness, and pain. For protection when handling solid urea, cotton or chemical resistant gloves and protective clothing are recommended. For eye protection, chemical safety goggles are recommended.

6.2.2.3 Inhalation

Provide fresh air. Give oxygen with assisted ventilation as required if cough/difficulty breathing occurs. Obtain medical attention if irritation persists.

Solid urea can create dust. Sufficient ventilation for enclosed areas should be provided so that airborne dust concentrations remain below OSHA limits for standard dust, or "nuisance" particles (15 mg/m^3). If a respirator is necessary, a NIOSH-approved respirator equipped with combined ammonia and dust, fume, and mist cartridges are suggested.

6.3 Environmental Impact Challenges and Barriers

Manufacturer's MSDSs describe urea as stable, non-carcinogenic, inflammable, and non-toxic to humans. However, the are certain conditions under which urea can pose safety and health problems. For example, although urea itself is not flammable or toxic to humans, urea undergoes thermal decomposition at elevated temperatures to produce toxic and combustible gasses (*i.e.*, ammonia, carbon dioxide, and oxides of nitrogen). Also, urea is described as slightly explosive in the presence of reducing materials, explosive when mixed with hypochlorites, and non-explosive in other cases. Solid urea is likely to form dust, and should be handled accordingly with proper ventilation and respiratory protection.[67]

[65] Terra Nitrogen Corporation "MSDS for Urea (solid)." (www.terraindustries.com). 2001

[66] Industrial Resources Group, Inc. "MSDS for Urea 46-0-0 (solid)." (www.indresgroup.com), 2001

[67] Terra Nitrogen Corporation, "MSDS for Urea."

Safe handling, as described in Section 6.2, is important for minimizing these safety and health risks. As urea is already widely distributed as a fertilizer, the SCR-urea infrastructure participants would be expected to adopt the safe-handling procedures already established for the existing urea distribution pathways.

In anticipation of the new urea distribution pathways, future studies should determine the extent of safety training and educational materials (e.g., brochures, signs, and placards) that would be needed for staff that transport urea along new distribution pathways and handle urea at new transfer points. Additional study also is needed to determine the likelihood and impact of large urea spills, and the appropriate spill response measures that should be followed in case of such a spill.

7. Life-Cycle Greenhouse Gas Emissions

ADL estimated the marginal well–to-tank greenhouse gases (GHGs) for the four pathways selected in the life-cycle cost evaluation: Pathways 1, 4, 8, and 9. The GHGs included in the analysis were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The marginal change in vehicle GHG emissions was not estimated.

For each pathway, ADL included an estimate of emissions from fuel production and fuel use associated with each step of the manufacture, distribution, and dispensing of SCR-urea. The emissions factors were based on widely recognized data sources as well as previous studies performed by ADL. Table 7-1 summarizes the major information sources used in our evaluation.

Table 7-1. Emission Factor Sources

Data	Sources	Descriptions
Fuel Production Emission Factors	The Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model[68], Version 1.6, Argonne National Laboratory	The GREET model provides fuel and vehicle cycle emission and energy life-cycle estimates
Vehicle Emission Factors	• "EMFAC2000 Documentation", California Air Resources Board, 2000. • "Inventory of California Greenhouse Gas Emissions and Sinks: 1990-1999", California Energy Commission, 2001. • "Fuel Choices for a Hydrogen Infrastructure", Arthur D. Little, 2001.	• The ARB documentation provides the methodology and assumptions used in developing their latest on-road vehicle model EMFAC2000. • The CEC report is a documentation of the California GHG inventory methodology. • The ADL report provides the GHG emission factors for vehicles
Equipment Emission Factors	• "Notice of Public Meeting to Consider Approval of California's Emission Inventory for Offroad Large Compression Ignited Engine s(>25 hp) using the OFFROAD Model", California Air Resources Board	• The report presents the main characteristics of the large diesel equipment inventory

Each pathway's emission contribution was calculated in grams of pollutant per ton of urea produced, transported, or dispensed as applicable. The GHG results were then adjusted to the equivalent CO_2 emissions. The results are presented in Section 7.2.

7.1 Life-Cycle Emission Evaluation Assumptions

The following section summarizes the major assumptions that were made in order to estimate the lifecycle greenhouse gas emissions for the different urea distribution pathways. A total of nine urea distribution pathways were discussed in Section 4. Four

[68] Version 1.6, Argonne National laboratory.

pathways were chosen to represent the range of GHG emissions. Each pathway represents a major distribution channel and the key steps in each pathway are summarized in Table 7-2 based on Table 4-5. Figure 7-1 illustrates the various GHG emission locations along the pathways.

The assumptions in the following sections are consistent with the cost estimates assumptions.

Table 7-2. Pathway Description

Pathway	1	4	8	9
Foreign Granular Urea	X			
Shipping	X			
Unloading	X			
Transport to plant	X			
Storage	X			
Bagging	X			
Bulk loading	X			
Manufacture at plant		X	X	X
Urea Liquor (70% solution)			X	X
Granular urea		X		
Blending at plant				
Loading at plant		X		
Transport from plant to terminal	X	X	X	
Unloading	X	X	X	
Storage	X	X	X	
Blending at terminal	X	X	X	
Loading	X	X	X	
Transport to truck-stop	X	X	X	X
Unloading	X	X	X	X
Storage	X	X	X	X
Blending				X
Dispensing	X	X	X	X

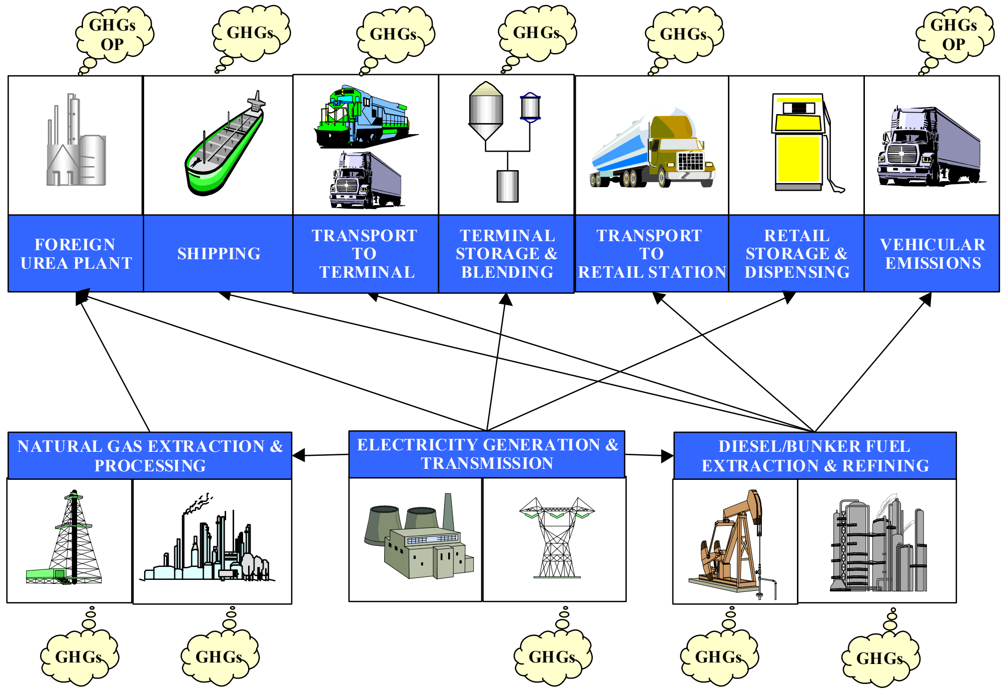


Figure 7-1. GHG Emissions Along the Production and Distribution Pathways

Urea Production

For the sake of GHG estimation, the urea production process includes the extraction and processing of natural gas, transmission of the natural gas to the plant, conversion/reaction steps, the combustion of natural gas for steam, and electricity usage. The natural gas and electricity consumption estimates are based on a typical urea plant process' energy estimate (Kirk-Othmer, Chemical Tech. Encyclopedia). One major assumption is that only 5% of the steam used is provided by the combustion of natural gas. The rest is waste steam for the co-located ammonia plant. Production of urea liquor is estimated to be less energy intensive than the production of granular urea, which requires a few additional steps. The emissions for electricity use at the outlet-wall was estimated using GREET with the assumption of the United States' average electricity generation mix.

Urea Transport from Foreign Sources

It is assumed that urea transport from foreign sources will occur from the major urea exporters of the world (Gulf States, Former Soviet Union countries, and Venezuela) to the major ports in the United States on the Gulf Coast, California, Washington, and the

East Coast. The evaluation assumes that the ships travel an average distance of 7,500 miles with an average fuel consumption of 0.0018 kg of bunker fuel per ton-mile.[69]

Urea Transfer from Ship to Port to Train/Truck

Once the urea arrives to the ports it is unloaded from the ship and transferred to trucks and/or railcars for transportation the next destination, which may be a plant or a terminal. The freight transfer handling equipment typically consist of large electric gantry cranes, full and empty container forklifts, and tractors. The characteristic (horsepower) and usage rates (tons/hour) for these pieces of equipment were provided by the Air Resources Board off-road inventory documentation and a Port of Los Angeles representative[70].

Urea Transport to Terminal or Plant

Urea transportation within the United States, from the ports or plants to the terminals will occur by truck and rail. Trucks will be the main means of transport for distances less than 200 miles. Rail will be used for longer distances. Based on an overview of the potential locations of the urea redistribution terminals, it is assumed that the average distance for transportation by rail is 750 miles. Overall it is assumed, based on internal ADL estimates, that 50% of the urea will be transported by train and the remaining 50% will be transported by truck.

Urea Storage, Blending, and Transfer at Terminal or Plant

Table 7-3 summarizes the assumed electricity needed to store and blend the urea to a 32.5% solution. The electricity requirements are based on ADL internal estimates.

Table 7-3. Electricity Requirements for Storage, Blending, and Transfer

Process	Requirement (kWh/ton-Urea)
Storage Energy Requirements	2
Blending Energy Requirements	15
Transfer Energy Requirements	7
Total Electricity Requirements	24

[69] ADL report to the Department of Energy, "Fuel Choices for a Hydrogen Infrastructure." 2001.

[70] ADL communication with T. L. Garrett, Port of Los Angeles, February 2002.

Urea Transport to Truck Stop or Service Station

The average distance between the terminal or plant and the dispensing location is assumed to be 100 miles. Heavy-duty trucks are expected to transport the urea, mostly as a 32.5% aqueous solution, from the terminals to the retail points.

Urea Storage and Dispensing at Truck Stop or Service Station

Table 7-4 summarizes electricity requirements for storing and dispensing the 32.5% aqueous urea solution for SCR use.[71]

Table 7-4. Electricity Requirements for Urea Storage and Dispensing

Process	Requirement (kWh/ton-Urea)
Storage Energy Requirements	2
Dispensing Energy Requirements	5
Total Electricity Requirements	7

7.2 Life-cycle Emission Results

The following tables and figures present the results of the lifecycle emission analysis. Tables 7-5, 7-6, 7-7, and 7-8 provide pathway specific emissions in grams per ton of urea. Figure 7-2 provides a comparison of the greenhouse gas emissions in CO_2 equivalent grams per ton of urea.

Pathway 1, which involves the production and distribution of foreign granular urea, is estimated to produce the most greenhouse gas compared to the other pathways. The incremental emissions compared to other pathways include offshore shipping and port transfer operations.

Pathways 8 and 9 are estimated to produce less greenhouse gas emissions, mainly because these scenarios involve fewer transportation steps. However, these scenarios assume that the dispensing locations will be located within 100 miles of the urea liquor plant and are therefore less likely scenarios than Pathways 1 and 2.

Table 7-9 compares the GHG emissions produced by the urea production and use and the diesel production emission for a heavy-duty diesel vehicle. The diesel GHG emissions are preliminary results from an ongoing study by ADL for the CARB on life-cycle fuel-related emissions. The urea-related emissions include production and

[71] ADL internal estimates.

distribution, as well as CO_2 emissions from consumption in the SCR catalyst. As shown in Table 7-9, urea production, distribution, and use will add up to an estimated 1% of GHG emissions from diesel vehicles.

Table 7-5. Pathway 1 Life-cycle Greenhouse Gas Emissions

Pathway Step	Emissions (g/ton-Urea)		
	CH_4	N_2O	CO_2
Production	6,428	9	735,003
Offshore Shipping	57	0	55,445
Transfer	1	0	785
Domestic Transport to Terminal	13	1	28,045
Terminal Operation	65	1	45,129
Transport to Truck Stop	36	1	25,107
Truck Stop Operation	65	1	45,129
Total	6,700	13	934,600

Table 7-6. Pathway 4 Life-cycle Greenhouse Gas Emissions

Pathway Step	Emissions (g/ton-Urea)		
	CH_4	N_2O	CO_2
Production	6,428	9	735,003
Domestic Transport to Terminal	13	1	28,045
Terminal Operation	65	1	45,129
Transport to Truck Stop	36	1	25,107
Truck Stop Operation	65	1	45,129
Total	6,600	13	878,400

Table 7-7. Pathway 8 Life-cycle Greenhouse Gas Emissions

Pathway Step	Emissions (g/ton-Urea)		
	CH_4	N_2O	CO_2
Production	6,018	8	578,078
Domestic Transport to Terminal	19	1	29,025
Terminal Operation	65	1	45,129
Transport to Truck Stop	36	1	25,107
Truck Stop Operation	65	1	45,129
Total	6,200	11	722,500

Table 7-8. Pathway 9 Life-cycle Greenhouse Gas Emissions

Pathway Step	Emissions (g/ton-Urea)		
	CH_4	N_2O	CO_2
Production	6,018	8	578,078
Transport to Truck Stop	18	0	9,142
Blending Operation	65	1	45,129
Truck Stop Operation	65	1	45,129
Total	6,200	9	677,500

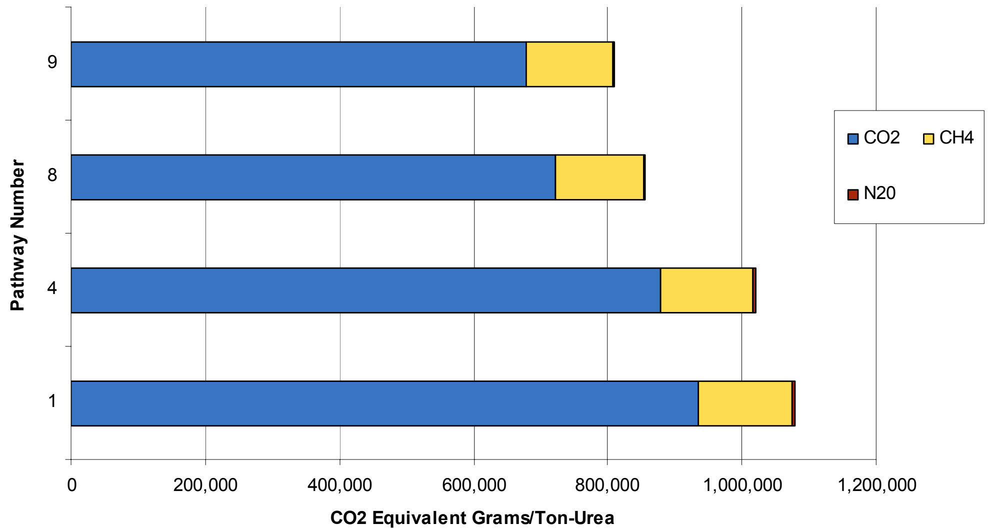


Figure 7-2. Pathway Greenhouse Gas Emission Estimates in grams CO_2 per Ton-Urea

Table 7-9. GHG Emissions Comparison

Sources	Urea Pathway 1	Urea Pathway 9	Diesel (HDV)
GHG Emissions (g CO_2/gallon diesel)	143	121	13,000

8. Conclusions

Future Federal emission standards recently adopted by EPA will require most diesel vehicle and engine manufacturers to implement advanced NO_x, hydrocarbon, and particulate matter controls. SCR is a proven stationary NO_x emission control technology that is currently being demonstrated for on-road heavy- and light-duty applications. Preliminary results have shown that SCR systems combining an SCR catalyst with oxidation catalysts and diesel particulate filters can meet future emission standards. On-road SCR systems will require an on-board supply of reductant. The most likely candidate for reductant is urea, a compound manufactured by combining ammonia with carbon dioxide under high pressure and used traditionally as a fertilizer.

Implementing urea as an SCR reductant will require the development of a urea production and distribution infrastructure. The current urea infrastructure that supplies urea to the agricultural sectors and the petroleum infrastructure that supplies diesel to the retail sector are potential models for SCR-urea distribution. Assuming that all new diesel vehicles meeting MY2007+ federal emission standards use SCR systems, urea production facilities in the United States and worldwide could be used to provide the estimated 700,000 tons urea per year required to meet the 2010 on-road SCR-urea demand. Foreign urea might be used to meet incremental urea demand depending on the market price of natural gas, the main feedstock for ammonia and urea production. However, current uncertainties regarding the characteristics of the urea (purity, additives, etc.) required for SCR systems limit our assessment of the extent to which current infrastructure will be used to produce, transport, and store SCR-urea.

ADL considered nine distribution pathways that encompass the most likely pathways, as well as existing distribution channels. These pathways help identify the elements of the TS&D infrastructure network that currently do not exist, such as blending equipment, retail storage, and dispensing equipment. These pathways also help determine potential points of cross-contamination and segregated storage requirements. Infrastructure costs at the retail level represent the major parts of the distribution costs. Based on the pathway assumptions, the cost of distributing urea can range from $0.70 to $35/gallon depending on the volume of urea distributed throughout the system, the number of retail points, and the level of product segregation required. The lower end of the price range represents urea distribution focused at truck stops serving a large population of SCR-equipped vehicles, while the upper part of the price range represents urea distribution at light-duty retail outlets with low urea throughput.

Dispensing equipment costs represent the major part of the distribution costs. Due to economies of scale, distribution costs—and therefore overall retail costs—are reduced if SCR-urea dispensing infrastructure is installed in fewer retail stations with relatively higher urea throughput. Assuming a demand of approximately 1 million tons of SCR-urea, the distribution cost can increase by a factor of 10 if the number of retail stations dispensing SCR-urea is increased. In addition, production costs are expected to range between $0.12 to $0.30/gallon of SCR-urea solution. Markup along the supply chain can be between $0.05 to $0.10/gal based on typical diesel supply chain mark-ups.

The potential magnitude of spills along the TS&D pathways was also examined. As urea is a widely transported product, the handling precautions and spill cleanup procedures are well documented. Although most of the pathway elements currently handle urea, this information will need to be adapted for retail urea dispensing locations.

The life-cycle greenhouse gas impacts of the urea TS&D pathways were estimated at up to 1% of the current diesel heavy-duty vehicle life-cycle greenhouse emissions.

To the extent that current urea grades can be used to produce SCR-urea, the short- to mid-term implementation of an SCR-urea infrastructure will not be limited by the availability of urea or the need for a distribution network. Further studies aimed at developing an SCR-urea specification should determine the need for refined production and TS&D processes that avoid cross-contamination from other urea grades and contamination from transport and storage tanks. Issues that require further study include the availability of appropriate dispensing and storage equipment at the retail level, the level of penetration of SCR-urea at the retail stations, the life-cycle cost implications to the diesel vehicles or fleets using SCR, as well as life-cycle criteria pollutant cost evaluations.

Appendix A. Urea Stoichiometric Analysis

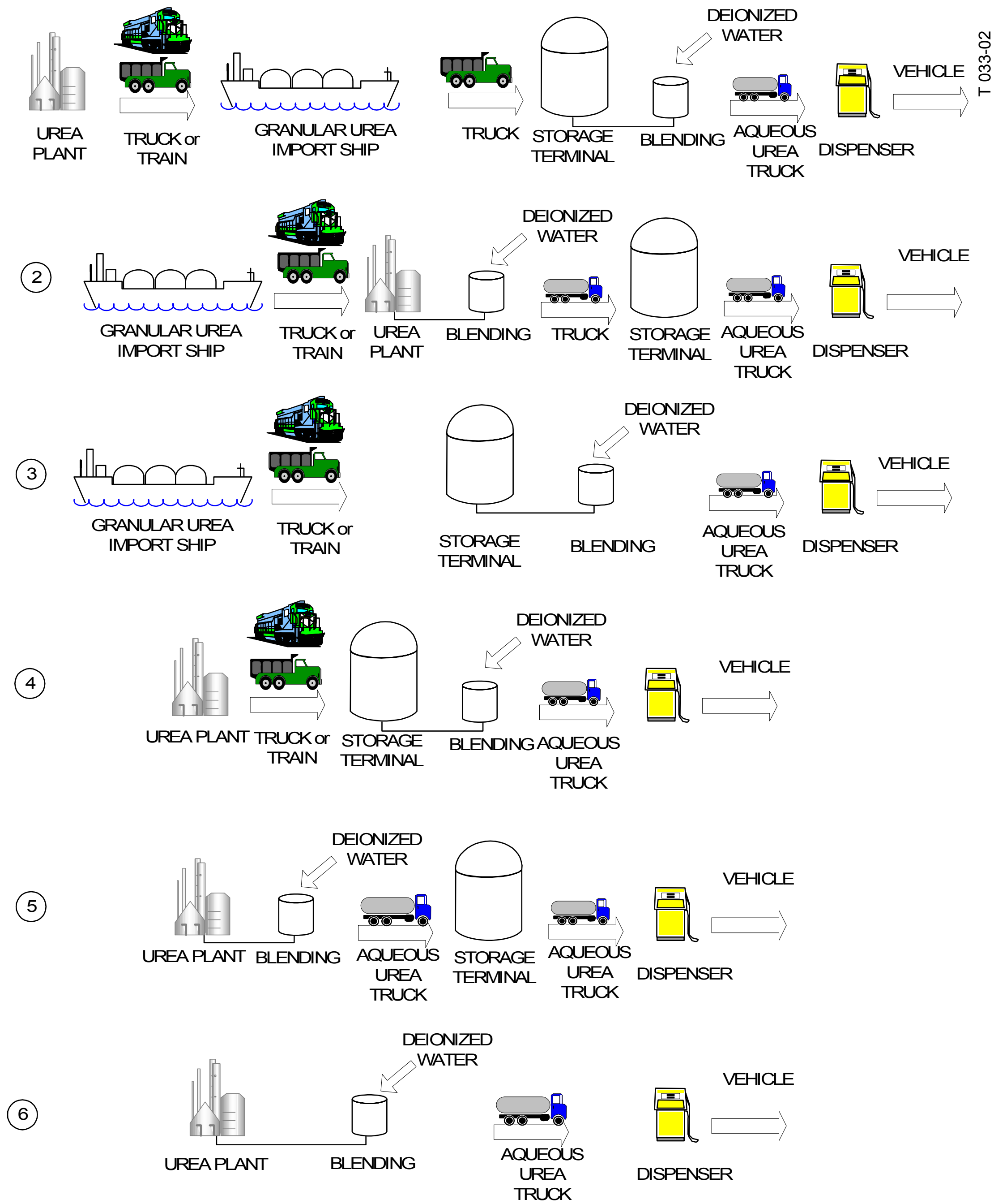
Urea to Diesel Consumption Ratio, Using Stochiometry and Other Parameters

SCR efficiency	NO_2 fraction of NO_X	HD NO_x emissions baseline (g/bhp-hr)	HD NO_x emissions reduced (g/bhp-hr)	HD fuel economy (bhp-hr/gallon)	HD diesel to 32.5%wt urea (volume ratio)	LD NO_x emissions baseline (g/mile)	LD NO_x emissions reduced (g/mile)	LD fuel economy (mpg)	LD diesel to 32.5%wt urea (volume ratio)
100%	80%	4	0.2	17	23.2	1.5	0.2	25	46.1
100%	90%	4	0.2	17	23.5	1.5	0.2	25	46.8
90%	80%	4	0.2	17	20.9	1.5	0.2	25	41.5
90%	90%	4	0.2	17	21.2	1.5	0.2	25	42.1
80%	80%	4	0.2	17	18.6	1.5	0.2	25	36.9
80%	90%	4	0.2	17	18.8	1.5	0.2	25	37.4
50%	80%	4	0.2	17	11.6	1.5	0.2	25	23.1
50%	90%	4	0.2	17	11.8	1.5	0.2	25	23.4
100%	80%	4	0.2	18.5	21.3	1.5	0.07	30	34.9
100%	90%	4	0.2	18.5	21.6	1.5	0.07	30	35.5
90%	80%	4	0.2	18.5	19.2	1.5	0.07	30	31.4
90%	90%	4	0.2	18.5	19.5	1.5	0.07	30	31.9
80%	80%	4	0.2	18.5	17.1	1.5	0.07	30	28.0
80%	90%	4	0.2	18.5	17.3	1.5	0.07	30	28.4
50%	80%	4	0.2	18.5	10.7	1.5	0.07	30	17.5
50%	90%	4	0.2	18.5	10.8	1.5	0.07	30	17.7
100%	80%	4	0.2	20	19.7	1.5	0.02	40	25.3
100%	90%	4	0.2	20	20.0	1.5	0.02	40	25.7
90%	80%	4	0.2	20	17.8	1.5	0.02	40	22.8
90%	90%	4	0.2	20	18.0	1.5	0.02	40	23.1
80%	80%	4	0.2	20	15.8	1.5	0.02	40	20.3
80%	90%	4	0.2	20	16.0	1.5	0.02	40	20.6
50%	80%	4	0.2	20	**9.9**	1.5	0.02	40	**12.7**
50%	90%	4	0.2	20	10.0	1.5	0.02	40	12.8
100%	80%	2.5	0.2	17	38.3	1	0.2	25	75.0
100%	90%	2.5	0.2	17	38.9	1	0.2	25	76.1
90%	80%	2.5	0.2	17	34.5	1	0.2	25	67.5
90%	90%	2.5	0.2	17	35.0	1	0.2	25	68.5
80%	80%	2.5	0.2	17	30.7	1	0.2	25	60.0
80%	90%	2.5	0.2	17	31.1	1	0.2	25	60.8
50%	80%	2.5	0.2	17	19.2	1	0.2	25	37.5
50%	90%	2.5	0.2	17	19.5	1	0.2	25	38.0
100%	80%	2.5	0.2	18.5	35.2	1	0.07	30	53.7
100%	90%	2.5	0.2	18.5	35.8	1	0.07	30	54.5
90%	80%	2.5	0.2	18.5	31.7	1	0.07	30	48.4
90%	90%	2.5	0.2	18.5	32.2	1	0.07	30	49.1
80%	80%	2.5	0.2	18.5	28.2	1	0.07	30	43.0
80%	90%	2.5	0.2	18.5	28.6	1	0.07	30	43.6
50%	80%	2.5	0.2	18.5	17.6	1	0.07	30	26.9
50%	90%	2.5	0.2	18.5	17.9	1	0.07	30	27.3
100%	80%	2.5	0.2	20	32.6	1	0.02	40	38.2
100%	90%	2.5	0.2	20	33.1	1	0.02	40	38.8
90%	80%	2.5	0.2	20	29.3	1	0.02	40	34.4
90%	90%	2.5	0.2	20	29.8	1	0.02	40	34.9
80%	80%	2.5	0.2	20	26.1	1	0.02	40	30.6
80%	90%	2.5	0.2	20	26.5	1	0.02	40	31.0
50%	80%	2.5	0.2	20	16.3	1	0.02	40	19.1
50%	90%	2.5	0.2	20	16.5	1	0.02	40	19.4

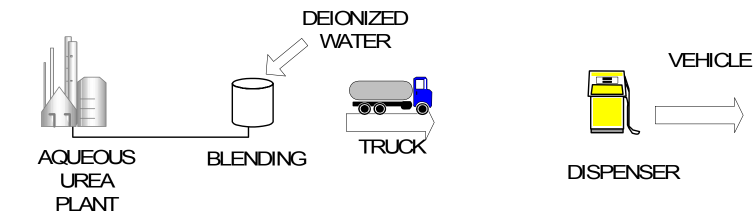
100%	80%	2	0.2	17	49.0	0.5	0.2	25	199.9
100%	90%	2	0.2	17	**49.7**	0.5	0.2	25	**202.8**
90%	80%	2	0.2	17	44.1	0.5	0.2	25	179.9
90%	90%	2	0.2	17	44.7	0.5	0.2	25	182.5
80%	80%	2	0.2	17	39.2	0.5	0.2	25	159.9
80%	90%	2	0.2	17	39.8	0.5	0.2	25	162.3
50%	80%	2	0.2	17	24.5	0.5	0.2	25	99.9
50%	90%	2	0.2	17	24.9	0.5	0.2	25	101.4
100%	80%	2	0.2	18.5	45.0	0.5	0.07	30	116.2
100%	90%	2	0.2	18.5	45.7	0.5	0.07	30	117.9
90%	80%	2	0.2	18.5	40.5	0.5	0.07	30	104.6
90%	90%	2	0.2	18.5	41.1	0.5	0.07	30	106.1
80%	80%	2	0.2	18.5	36.0	0.5	0.07	30	93.0
80%	90%	2	0.2	18.5	36.5	0.5	0.07	30	94.3
50%	80%	2	0.2	18.5	22.5	0.5	0.07	30	58.1
50%	90%	2	0.2	18.5	22.8	0.5	0.07	30	59.0
100%	80%	2	0.2	20	41.6	0.5	0.02	40	78.1
100%	90%	2	0.2	20	42.3	0.5	0.02	40	79.2
90%	80%	2	0.2	20	37.5	0.5	0.02	40	70.3
90%	90%	2	0.2	20	38.0	0.5	0.02	40	71.3
80%	80%	2	0.2	20	33.3	0.5	0.02	40	62.5
80%	90%	2	0.2	20	33.8	0.5	0.02	40	63.4
50%	80%	2	0.2	20	20.8	0.5	0.02	40	39.0
50%	90%	2	0.2	20	21.1	0.5	0.02	40	39.6
				max ratio	49.7			**max ratio**	202.8
				min	16.3			**min**	12.7

mols NH3 per mol urea	2
grams per mol NH3	17
grams per mol urea	60
mols NH3 per mol NO	1
mols NH3 per mol NO2	1.3
grams NO per mol NO	30
grams NO2per mol NO2	46
short tons urea per 32.5%wt urea	0.0015
grams per short ton	907185
grams urea per gallon 32.5%wt urea	1343

Appendix B. SCR Pathways



7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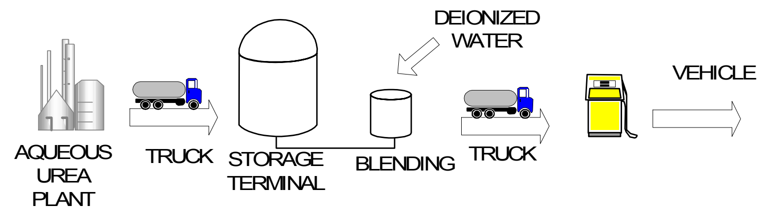
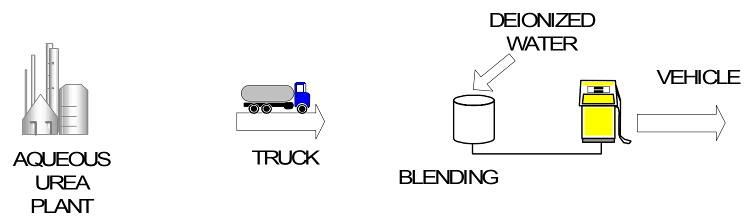
WATER
VEHICLE
AQUEOUS
UREA
PLANT
BLENDING
TRUCK
DISPENSER

8


DEIONIZED
WATER
VEHICLE
AQUEOUS
UREA
PLANT
TRUCK
STORAGE
TERMINAL
BLENDING
TRUCK

9


DEIONIZED
WATER
VEHICLE
AQUEOUS
UREA
PLANT
TRUCK
BLENDING

Appendix C. Transportation Assumptions

		Units	Bulk	Bagged
1	**International Shipment**	**Units**	**Bulk**	**Bagged**
	Total annual shipment	Tons/yr	1,000,000	1,000,000
	Average distance from international to domestic port	mi	7500	7500
	Average fertilizer bulk cargo ship capacity	DWT	50000	30000
	Cargo carrying factor		0.5	0.5
	Urea carrying capacity	Ton/ship	25000	15000
	# of shipments to the US (100% urea)	shipments/yr	40	67
	# of shipments to the US (50% urea)	shipments/yr	80	133
	Total distance traveled	shipment-miles	300,000	500,000
	Average price of international shipment	$/ton-mile	0.0075	0.0075
	Additional cost for special bagging (1/2 ton modules)	$/ton	10	10
	Additional cost for special bagging (1/2 ton modules)	$/ton-mile	0.0013	0.0013
	Total overseas shipping cost	$/ton-mile	0.009	0.009
2	**Transfer charges @ domestic ports**	$/ton	4	4

Ref. for 1 & 2:

a Lexis-Nexis, "Statistical Universe"
Urea Fertilizer Carbamide - Russian Producers - market
b Trends; www.peterpalms.com/fertilizer.html
c "K" Line Shipping Company, Japan

3	**Truck shipments to terminals & plants from ports**		**Bulk**	**Bagged**
	Total annual shipments (70% capacity)	Tons/yr	500,000	500,000
	Average shipment cost	$/ton-mile	0.08	0.08
	Load per truck	ton/truck	25	20
	# of trips	trips/yr	20,000	25,000
	Average time for transport	days/trip	0.3	0.3
	Average working days	days	250	250
	Average trips/day	trips/day	80	100
	# of truck trips per 12 hour day		1.5	1.5
	# of trucks required		53	67
	Price per truck	$	150,000	150,000
	Container per truck	$	100,000	20,000
	Transfer cost	$/ton	4	4
	Average Distance	Miles	150	150
	Nominal Distance	Miles /year	3,000,000	3,750,000
	Average cost per truck-trip/shipment	$/ton	12	12
	Transfer cost	$/ton	4	1
	Special bagging costs	$/ton	8	10

4	**SCR urea (liq.) by truck**		**Truck-Stop**	**Service Station**
	Total annual shipments (urea wt. basis)	ton/year	1,000,000	78,000
		gal/year	675,675,676	52,702,703
	liq. wt. basis	ton/yr	6,148,648,649	479,594,595
	Average shipment cost	$/ton-mile	0.1	0.1
	Weight of urea per truck (see "parameters" tab)	ton/truck	11.54	11.54
	# of trips	trips/yr	86,625	6,757
	Average working days	days	250	250
	Average trips/day	trips/day	347	27
	# of truck trips per 12 hour day		1.50	1.00
	# of trucks required		231	27
	Price per truck	$	150,000	150,000
	Container per truck	$	30,000	30,000
	Average Distance	Miles	100	250
	Nominal Distance	Miles /year	8,662,509	1,689,189
	Average cost per truck-trip/shipment	$/ton	10	25
	Transfer cost	$/ton	4	4
	Total cost per truck-trip/shipment	**$/ton**	**14**	**29**

Ref. for 3 & 4:

a Lexis-Nexis, "Statistical Universe"
b Data ffrom previous ADL studies

5 **Railroad Shipments**		**Bulk**	**Bagged**
Total annual shipments (30% capacity)	Tons/yr	500,000	500,000
Average shipment cost	$/ton-mile	0.023	0.023
Average load per car	ton/carload	63	63
Average load per train (20%)	ton/train	580	580
# of urea cars per train	cars/train	9.21	9.21
# of trips	trips/yr	862	862
Average time for transport	days/trip	3.0	3.0
Average working days	days	250	250
Average trips/day	trips/day	3	3
Trips by 1-train per year, 250 days	trips/year	83	83
# of trains required		10.34	10
# of cars required		95	95
Price per car	$	250,000	75,000
Special bagging costs	$/ton	0	10
Transfer cost	$/ton	4	4
Average Distance per trip	Miles	750	750
Nominal Distance	Miles /year	646,552	646,552
Average shipping cost	$/ton-mile	0.03	0.03
Average cost per rail-trip/shipment	$/ton	17.25	17.25
Transfer cost	$/ton	4	4
Total cost	**$/ton**	**21.25**	**21.25**

Ref. for 5:

a Lexis-Nexis, "Statistical Universe"

b Class I Railroad Statistics - American Association of Railroads, April 2002

c Data from previous ADL studies

Appendix D.

Urea Transportation Costs; 1,000,000 tons/year; all purities		Overseas shipping; bulk	Overseas shipping; bagged	Truck, Port to Plant or terminal; bulk	Truck, Port to Plant or terminal; bagged	Railroad, Port to Plant or terminal; bulk	Railroad, Port to Plant or terminal; bagged	Truck, Plant or terminal to retail truck-stop; 32% liq. urea	Truck, Plant or terminal to retail station - 32% liq. urea - LDV
	Units								
Capital Costs									
Purchased Equipment									
Solid urea containers	$	0	0	0	0	0	0	0	0
SCR urea (liq.) tanks	$	0	0	0	0	0	0	0	0
Agitators/Stirrer - lined recirculation pump	$	0	0	0	0	0	0	0	0
Tank Heaters - external resistance heaters	$	0	0	0	0	0	0	0	0
Balance of Plant (S&D) Equipment, 10%	$	0	0	0	0	0	0	0	0
Sub-total Purchased Equipment Cost	$	0	0	0	0	0	0	0	0
Freight and Taxes (8%)	$	0	0	0	0	0	0	0	0
Total Purchased Equipment Cost	$	0	0	0	0	0	0	0	0
Installation Costs (equipment installation)	$	0	0	0	0	0	0	0	0
Indirect Installation Costs (engr, office, etc.)	$	0	0	0	0	0	0	0	0
Total Installation Costs	$	0	0	0	0	0	0	0	0
Total Installed Cost	$	0	0	0	0	0	0	0	0
Administrative Costs (Office, permitting, Trng,etc.), ~10% of installed cost	$	0	0	0	0	0	0	0	0
Total Capital Investment, $	**$**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Annual Operating Costs, per ton of urea basis									
Average cost per shipment	$/ton	68	70	20	20	21	21	14	30
Other costs (admin, trng, etc.) , 10% of transportation costs	$/ton	7	7	2	2	2	2	1	3
Total Annual Costs	$/ton	75	77	22	22	23	23	15	33
Capital Recovery (3-year, 10%),	$	0	0	0	0	0	0	0	0
	$/ton	0	0	0	0	0	0	0	0
Annualized Total Cost, $/ton	**$/ton**	**75**	**77**	**22**	**22**	**23**	**23**	**15**	**33**

	ASSUMPTIONS									
	Transportation mode capacity distribution									
	ship		100%	100%	---	---	---	---	---	---
	train		---	---	---	---	50%	50%	---	---
	truck		---	---	50%	50%	---	---	100%	100%
1	Annual quantity of SCR grade solid urea transported	tons	1,000,000	1,000,000	500,000	500,000	500,000	500,000	1,000,000	78,000
2	Average distance of transportation	mi	7500	7500	200	200	750	750	100	250
3	Average capacity (cargo, rail-car load, ruck-load, etc.)	tons	25000	15000	25	20	63	55	25	25
4	Average capacity solid urea basis	tons							11.54	11.54
4	Average capacity per train	tons	---	---	---	---	580	580		
4	# of shipments to domestic ports (full load = urea)	shipments/year	40	67	---	---	---	---		
5	# of truck/rail trips per year	trips/year	---	---	20,000	25,000	862	862	86,655	6,759
6	Average round-trip time	days	---	---	0.30	0.30	3	3	0.3	1
7	Average working days per year	days	---	---	250	250	250	250	250	250
8	Average length of operation of truck per day	hr	---	---	12	12	---	---	12	12
9	# of trucks/trains required for SCR urea service		---	---	53	67	10	10	347	27
10	# of urea rail-cars per train	rail-cars/train	---	---	---	---	9.2	10.5		
11	Price of container/rail-car (pneumatic transfer containers)	$/truck	---	---	100,000	-	250,000	0	30,000	30,000
12	Average shipping price	$/ton-mile	0.0075	0.0075	0.08	0.08	0.023	0.023	0.1	0.1
13	Average cost of special ship-containers and/or special bagging	$/ton	8	10	0	0	0	0	0	0
		$/ton-mile	0.0011	0.0013	0	0	0	0	0	0
14	Sum of transportation charges	$/ton-mile	0.009	0.009	0.08	0.08	0.023	0.023	0.1	0.1
		$/ton	64.3	66.3	16	16	17.25	17.25	10	25
15	Loading/Unloading charges (transfer charges)	$/ton	4	4	4	4	4	4	4	5
16	Average cost per shipment	$/ton	68.3	70.3	20.0	20.0	21.3	21.3	14	30
	Assumptions:									
17	Estimate Equivalent Level Cost using the Capital Recovery Factor									
	Inerest Rate, i		10%	10%	10%	10%	10%	10%	10%	10%
	Time Period in Years, n		3	3	3	3	3	3	3	3
	Capital Recovery Factor, CRF		0.402	0.402	0.402	0.402	0.402	0.402	0.402	0.402

Urea Transportation Costs; 4,000,000 tons/year; high purity	Units	Overseas shipping; bulk	Overseas shipping; bagged	Truck, Port to Plant or terminal; bulk	Truck, Port to Plant or terminal; bagged	Railroad, Port to Plant or terminal; bulk	Railroad, Port to Plant or terminal; bagged	Truck, Plant or terminal to retail truck-stop; 32% liq. urea	Truck, Plant or terminal to retail station - 32% liq. urea - LDV
Capital Costs									
Purchased Equipment									
Solid urea containers	$	0	0	21,333,333	0	95,238,095	0	41,594,454	3,244,367
SCR urea (liq.) tanks	$	0	0	0	0	0	0	0	0
Agitators/Stirrer - lined recirculation pump	$	0	0	0	0	0	0	1,500	1,500
Tank Heaters - external resistance heaters	$	0	0	0	0	0	0	500	500
Balance of Plant (S&D) Equipment, 10%	$	0	0	2,133,333	0	9,523,810	0	20,798,227	1,623,184
Sub-total Purchased Equipment Cost	$	0	0	23,466,667	0	104,761,905	0	62,392,681	4,867,551
Freight and Taxes (8%)	$	0	0	1,877,333	0	8,380,952	0	4,991,414	389,404
Total Purchased Equipment Cost	$	0	0	25,344,000	0	113,142,857	0	67,384,096	5,256,955
Installation Costs (equipment installation)	$	0	0	5,068,800	0	11,314,286	0	16,846,024	1,314,239
Indirect Installation Costs (engr, office, etc.)	$	0	0	506,880	0	1,131,429	0	1,684,602	131,424
Total Installation Costs	$	0	0	5,575,680	0	12,445,714	0	18,530,626	1,445,663
Total Installed Cost	$	0	0	30,919,680	0	125,588,571	0	85,914,722	6,702,618
Administrative Costs (Office, permitting, Trng,etc.), ~10% of installed cost	$	0	0	3,091,968	0	12,558,857	0	8,591,472	670,262
Total Capital Investment, $	**$**	**0**	**0**	**34,011,648**	**0**	**138,147,429**	**0**	**94,506,194**	**7,372,880**
Annual Operating Costs, per ton of urea basis									
Average cost per shipment	$/ton	68	70	20	20	21	21	14	30
Other costs (admin, trng, etc.) , 10% of transportation costs	$/ton	7	7	2	2	2	2	1	3
Total Annual Costs	$/ton	75	77	22	22	23	23	15	33
Capital Recovery (3-year, 10%),	$	0	0	13,676,587	0	55,551,126	0	38,002,340	2,964,744
	$/ton	0	0	7	0	28	0	10	10
Annualized Total Cost, $/ton	**$/ton**	**75**	**77**	**29**	**22**	**51**	**23**	**25**	**43**

ASSUMPTIONS

	Transportation mode capacity distribution									
	ship		100%	100%	---	---	---	---	---	---
	train		---	---	---	---	50%	50%	---	---
	truck		---	---	50%	50%	---	---	100%	100%
1	Annual quantity of SCR grade solid urea transported	tons	4,000,000	4,000,000	2,000,000	2,000,000	2,000,000	2,000,000	4,000,000	312,000
2	Average distance of transportation	mi	7500	7500	200	200	750	750	100	250
3	Average capacity (cargo, rail-car load, ruck-load, etc.)	tons	25000	15000	25	20	63	55	25	25
4	Average capacity solid urea basis	tons							11.54	11.54
4	Average capacity per train	tons	---	---	---	---	580	580		
4	# of shipments to domestic ports (full load = urea)	shipments/year	160	267	---	---	---	---		
5	# of truck/rail trips per year	trips/year	---	---	80,000	100,000	3,448	3,448	346,620	27,036
6	Average round-trip time	days	---	---	0.30	0.30	3	3	0.3	1
7	Average working days per year	days	---	---	250	250	250	250	250	250
8	Average length of operation of truck per day	hr	---	---	12	12	---	---	12	12
9	# of trucks/trains required for SCR urea service		---	---	213	267	41	41	1,386	108
10	# of urea rail-cars per train	rail-cars/train	---	---	---	---	9.2	10.5		
11	Price of container/rail-car (pneumatic transfer containers)	$/truck	---	---	100,000	-	250,000	0	30,000	30,000
12	Average shipping price	$/ton-mile	0.0075	0.0075	0.08	0.08	0.023	0.023	0.1	0.1
13	Average cost of special ship-containers and/or special bagging	$/ton	8	10	0	0	0	0	0	0
		$/ton-mile	0.0011	0.0013	0	0	0	0	0	0
14	Sum of transportation charges	$/ton-mile	0.009	0.009	0.08	0.08	0.023	0.023	0.1	0.1
		$/ton	64.3	66.3	16	16	17.25	17.25	10	25
15	Loading/Unloading charges (transfer charges)	$/ton	4	4	4	4	4	4	4	5
16	Average cost per shipment	$/ton	68.3	70.3	20.0	20.0	21.3	21.3	14	30

Assumptions:

17	Estimate Equivalent Level Cost using the Capital Recovery Factor								
	Inerest Rate, i	10%	10%	10%	10%	10%	10%	10%	10%
	Time Period in Years, n	3	3	3	3	3	3	3	3
	Capital Recovery Factor, CRF	0.402	0.402	0.402	0.402	0.402	0.402	0.402	0.402

Urea Transportation Costs; 1,000,000 tons/year; high purity	Units	Overseas shipping; bulk	Overseas shipping; bagged	Truck, Port to Plant or terminal; bulk	Truck, Port to Plant or terminal; bagged	Railroad, Port to Plant or terminal; bulk	Railroad, Port to Plant or terminal; bagged	Truck, Plant or terminal to retail truck-stop; 32% liq. urea	Truck, Plant or terminal to retail station - 32% liq. urea - LDV
Capital Costs									
Purchased Equipment									
Solid urea containers	$	0	0	5,333,333	0	23,809,524	0	10,398,614	811,092
SCR urea (liq.) tanks	$	0	0	0	0	0	0	0	0
Agitators/Stirrer - lined recirculation pump	$	0	0	0	0	0	0	1,500	1,500
Tank Heaters - external resistance heaters	$	0	0	0	0	0	0	500	500
Balance of Plant (S&D) Equipment, 10%	$	0	0	533,333	0	2,380,952	0	5,200,307	406,546
Sub-total Purchased Equipment Cost	$	0	0	5,866,667	0	26,190,476	0	15,598,920	1,217,638
Freight and Taxes (8%)	$	0	0	469,333	0	2,095,238	0	1,247,914	97,411
Total Purchased Equipment Cost	$	0	0	6,336,000	0	28,285,714	0	16,846,834	1,315,049
Installation Costs (equipment installation)	$	0	0	1,267,200	0	2,828,571	0	4,211,708	328,762
Indirect Installation Costs (engr, office, etc.)	$	0	0	126,720	0	282,857	0	421,171	32,876
Total Installation Costs	$	0	0	1,393,920	0	3,111,429	0	4,632,879	361,638
Total Installed Cost	$	0	0	7,729,920	0	31,397,143	0	21,479,713	1,676,687
Administrative Costs (Office, permitting, Trng,etc.), ~10% of installed cost	$	0	0	772,992	0	3,139,714	0	2,147,971	167,669
Total Capital Investment, $	**$**	**0**	**0**	**8,502,912**	**0**	**34,536,857**	**0**	**23,627,685**	**1,844,356**
Annual Operating Costs, per ton of urea basis									
Average cost per shipment	$/ton	68	70	20	20	21	21	14	30
Other costs (admin, trng, etc.) , 10% of transportation costs	$/ton	7	7	2	2	2	2	1	3
Total Annual Costs	$/ton	75	77	22	22	23	23	15	33
Capital Recovery (3-year, 10%),	$	0	0	3,419,147	0	13,887,782	0	9,501,042	741,643
	$/ton	0	0	7	0	28	0	10	10
Annualized Total Cost, $/ton	**$/ton**	**75**	**77**	**29**	**22**	**51**	**23**	**25**	**43**

ASSUMPTIONS

Transportation mode capacity distribution									
ship		100%	100%	---	---	---	---	---	---
train		---	---	---	---	50%	50%	---	---
truck		---	---	50%	50%	---	---	100%	100%
1 Annual quantity of SCR grade solid urea transported	tons	1,000,000	1,000,000	500,000	500,000	500,000	500,000	1,000,000	78,000
2 Average distance of transportation	mi	7500	7500	200	200	750	750	100	250
3 Average capacity (cargo, rail-car load, ruck-load, etc.)	tons	25000	15000	25	20	63	55	25	25
4 Average capacity solid urea basis	tons							11.54	11.54
4 Average capacity per train	tons	---	---	---	---	580	580		
4 # of shipments to domestic ports (full load = urea)	shipments/year	40	67	---	---	---	---		
5 # of truck/rail trips per year	trips/year	---	---	20,000	25,000	862	862	86,655	6,759
6 Average round-trip time	days	---	---	0.30	0.30	3	3	0.3	1
7 Average working days per year	days	---	---	250	250	250	250	250	250
8 Average length of operation of truck per day	hr	---	---	12	12	---	---	12	12
9 # of trucks/trains required for SCR urea service		---	---	53	67	10	10	347	27
10 # of urea rail-cars per train	rail-cars/train	---	---	---	---	9.2	10.5		
11 Price of container/rail-car (pneumatic transfer containers)	$/truck	---	---	100,000	-	250,000	0	30,000	30,000
12 Average shipping price	$/ton-mile	0.0075	0.0075	0.08	0.08	0.023	0.023	0.1	0.1
13 Average cost of special ship-containers and/or special bagging	$/ton	8	10	0	0	0	0	0	0
	$/ton-mile	0.0011	0.0013	0	0	0	0	0	0
14 Sum of transportation charges	$/ton-mile	0.009	0.009	0.08	0.08	0.023	0.023	0.1	0.1
	$/ton	64.3	66.3	16	16	17.25	17.25	10	25
15 Loading/Unloading charges (transfer charges)	$/ton	4	4	4	4	4	4	4	5
16 Average cost per shipment	$/ton	68.3	70.3	20.0	20.0	21.3	21.3	14	30

Assumptions:

17 Estimate Equivalent Level Cost using the Capital Recovery Factor									
Inerest Rate, i		10%	10%	10%	10%	10%	10%	10%	10%
Time Period in Years, n		3	3	3	3	3	3	3	3
Capital Recovery Factor, CRF		0.402	0.402	0.402	0.402	0.402	0.402	0.402	0.402

Storage & Distribution (S&D) Costs @ Service-Station; Basis: 1,000,000 tons/year				
	Qty	Units		
Urea Purity			High	Low
Avg. UST size		gal	500	500
Capital Costs				
Purchased Equipment				
SCR Urea storage tanks	1	$	1,500	1,200
Agitators/Stirrer - lined recirculation pump	1	$	2,400	2,200
Tank Heaters - external resistance heaters	1	$	500	500
Pumps - centrifugal	2	$	2,000	1,500
Dispenser Equipment	1	$	7,500	7,500
Balance of Plant (S&D) Equipment, 50%		$	3,475	3,225
Sub-total Purchased Equipment Cost		$	17,375	16,125
Freight and Taxes (8%)		$	1,390	1,290
Total Purchased Equipment Cost		$	18,765	17,415
Installation Costs (equipment installation, construction)		$	37,530	34,830
Indirect Installation Costs (engr, office, etc.)		$	3,753	3,483
Total Installation Costs		$	41,283	38,313
Total Installed Cost		$	60,048	55,728
Administrative Costs (Office, permitting, trng,etc.), ~10% of installed cost		$	6,005	5,573
Total Capital Investment		**$**	**66,053**	**61,301**
Annual Operating Costs				
Labor		$/yr	2,190	2,190
Utility costs		$/yr	2,500	2,500
Subtotal, Operating Costs		$/yr	4,690	4,690
Overheads		$/yr	7,035	7,035
Capital Recovery		$/yr	26,561	24,650
Annualized Total Cost		**$/yr**	**33,596**	**31,685**
		$/ton	**23,631**	**22,287**
		$/gal	**34.97**	**32.98**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor	
	Inerest Rate, i	10%
	Time Period in Years, n	3
	Capital Recovery Factor, CRF	0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.	
3	Equipment costs were estimated using:	
	vendor information	
	proprietary web-based Chemical Process Engineering software	
	EA Engineering, Science & Technology, Inc's., Methanol Refueling Station Report, Feb 1999, for American Methanol Inst.	
4	Assume an underground storage tank, insulated, heated and corrosion protected	
5	Number of diesel retailing service-stations	55,300
6	SCR Urea throughput per service-station, gal/day	2.63
	gal/yr	961
	ton/yr (solid urea basis)	1
	Urea by wt in 32%, lb-urea/gal	2.96
7	Annual total urea consumption, MMtons	0.078

Storage & Distribution (S&D) Costs @ Service-Station; Basis: 4,000,000 tons/year				
	Qty	**Units**		
Urea Purity			**High**	**Low**
Avg. UST size		gal	500	500
Capital Costs				
Purchased Equipment				
SCR Urea storage tanks	1	$	1,500	1,200
Agitators/Stirrer - lined recirculation pump	1	$	2,400	2,200
Tank Heaters - external resistance heaters	1	$	500	500
Pumps - centrifugal	2	$	2,000	1,500
Dispenser Equipment	1	$	7,500	7,500
Balance of Plant (S&D) Equipment, 50%		$	3,475	3,225
Sub-total Purchased Equipment Cost		$	17,375	16,125
Freight and Taxes (8%)		$	1,390	1,290
Total Purchased Equipment Cost		$	18,765	17,415
Installation Costs (equipment installation, construction)		$	37,530	34,830
Indirect Installation Costs (engr, office, etc.)		$	3,753	3,483
Total Installation Costs		$	41,283	38,313
Total Installed Cost		$	60,048	55,728
Administrative Costs (Office, permitting, trng,etc.), ~10% of installed cost		$	6,005	5,573
Total Capital Investment		**$**	**66,053**	**61,301**
Annual Operating Costs				
Labor		$/yr	2,190	2,190
Utility costs		$/yr	2,500	2,500
Subtotal, Operating Costs		$/yr	4,690	4,690
Overheads		$/yr	7,035	7,035
Capital Recovery		$/yr	26,561	24,650
Annualized Total Cost		**$/yr**	**33,596**	**31,685**
		$/ton	**3,107**	**2,931**
		$/gal	**4.60**	**4.34**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor	
	Inerest Rate, i	10%
	Time Period in Years, n	3
	Capital Recovery Factor, CRF	0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.	
3	Equipment costs were estimated using: vendor information; proprietary web-based Chemical Process Engineering software; Refueling Station Report, Feb 1999, for American Methanol Inst.	
4	Assume an underground storage tank, insulated, heated and corrosion protected	
5	Number of diesel retailing service-stations	55,300
6	SCR Urea throughput per service-station, gal/day	20
	gal/yr	7305
	ton/yr (solid urea basis)	11
	Urea by wt in 32%, lb-urea/gal	2.96
7	Annual total urea consumption, MMtons	0.58

Storage & Distribution (S&D) Costs @ Truck-Stop and Fleet Station; Basis: 4,000,000 tons/year				
	Qty	**Units**		
Urea Purity			**High**	**Low**
Avg. UST size		gal	7,500	7,500
Capital Costs				
Purchased Equipment				
SCR Urea storage tanks	1	$	7,700	4,800
Agitators/Stirrer - lined recirculation pump	1	$	8,000	6,900
Tank Heaters - external resistance heaters	1	$	500	500
Pumps - centrifugal	2	$	6,000	6,000
Dispenser Equipment	5	$	37,500	37,500
Balance of Plant (S&D) Equipment, 50%		$	14,925	13,925
Sub-total Purchased Equipment Cost		$	74,625	69,625
Freight and Taxes (8%)		$	5,970	5,570
Total Purchased Equipment Cost		$	80,595	75,195
Installation Costs (equipment installation, construction)		$	80,595	75,195
Indirect Installation Costs (engr, office, etc.)		$	8,060	7,520
Total Installation Costs		$	88,655	82,715
Total Installed Cost		$	169,250	157,910
Administrative Costs (Office, permitting, trng,etc.), ~10% of installed cost		$	16,925	15,791
Total Capital Investment		**$**	**186,174**	**173,700**
Annual Operating Costs				
Labor		$/yr	2,190	2,190
Utility costs		$/yr	2,500	2,500
Subtotal, Operating Costs		$/yr	4,690	4,690
Overheads		$/yr	7,035	7,035
Capital Recovery		$/yr	74,864	69,848
Annualized Total Cost		**$/yr**	**81,899**	**76,883**
		$/ton	**451**	**424**
		$/gal	**0.67**	**0.63**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor	
	Inerest Rate, i	10%
	Time Period in Years, n	3
	Capital Recovery Factor, CRF	0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.	
3	Equipment costs were estimated using:	
	vendor information	
	proprietary web-based Chemical Process Engineering software	
	EA Engineering, Science & Technology, Inc's., Methanol Refueling Station Report, Feb 1999, for American Methanol Inst.	
4	Assume an underground storage tank, insulated, heated and corrosion protected	
5	Number of truck-stops	4,750
6	Number of fleet-stations	5,000
7	Monthly diesel consumption per truck-stop, gal/month	184,000
8	SCR Urea throughput per truck-stop, gal/day	336
	gal/yr	122,616
	ton/yr (solid urea basis)	181
	Urea by wt in 32%, lb-urea/gal	2.96
9	Annual total urea consumption, MMtons	3.3

Storage & Distribution (S&D) Costs @ Truck-Stop and Fleet Station; Basis: 1,000,000 tons/year				
	Qty	Units		
Urea Purity			**High**	**Low**
Avg. UST size		gal	1,000	1,000
Capital Costs				
Purchased Equipment				
SCR Urea storage tanks	1	$	3,000	2,200
Agitators/Stirrer - lined recirculation pump	1	$	2,400	2,200
Tank Heaters - external resistance heaters	1	$	500	500
Pumps - centrifugal	2	$	3,000	3,000
Dispenser Equipment	5	$	37,500	37,500
Balance of Plant (S&D) Equipment, 50%		$	11,600	11,350
Sub-total Purchased Equipment Cost		$	58,000	56,750
Freight and Taxes (8%)		$	4,640	4,540
Total Purchased Equipment Cost		$	62,640	61,290
Installation Costs (equipment installation, construction)		$	62,640	61,290
Indirect Installation Costs (engr, office, etc.)		$	6,264	6,129
Total Installation Costs		$	68,904	67,419
Total Installed Cost		$	131,544	128,709
Administrative Costs (Office, permitting, trng,etc.), ~10% of installed cost		$	13,154	12,871
Total Capital Investment		**$**	**144,698**	**141,580**
Annual Operating Costs				
Labor		$/yr	2,190	2,190
Utility costs		$/yr	1,750	1,750
Subtotal, Operating Costs		$/yr	3,940	3,940
Overheads		$/yr	4,925	4,925
Capital Recovery		$/yr	58,185	56,931
Annualized Total Cost		**$/yr**	**63,110**	**61,856**
		$/ton	**1,739**	**1,704**
		$/gal	**2.57**	**2.52**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor	
	Inerest Rate, i	10%
	Time Period in Years, n	3
	Capital Recovery Factor, CRF	0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.	
3	Equipment costs were estimated using:	
	vendor information	
	proprietary web-based Chemical Process Engineering software	
	EA Engineering, Science & Technology, Inc's., Methanol Refueling Station Report, Feb 1999, for American Methanol Inst.	
4	Assume an underground storage tank, insulated, heated and corrosion protected	
5	Number of truck-stops	4,750
6	Number of fleet-stations	5,000
7	Monthly diesel consumption per truck-stop, gal/month	36,800
8	SCR Urea throughput per truck-stop, gal/day	67
	gal/yr	24,523
	ton/yr (solid urea basis)	36
	Urea by wt in 32%, lb-urea/gal	2.96
9	Annual total urea consumption, MMtons	0.657

Blending & Storage Costs @ Terminal/Plant Level Basis:4,000,000 tons/year				
	Qty	**Units**	**Cost**	
Capital Costs				
Urea Purity			**High**	**Low**
Purchased Equipment				
Storage hoppers for solid urea - lined,50 ton (2000 ft3) cap. each	2	$	67,000	25,000
Transfer equipment - screw feeders, lined		$	2,400	2,400
Liq. SCR-urea storage tanks, lined, 7500 gal	1	$	25,700	16,100
Agitators/Stirrer - lined, 10 HP		$	8,000	6,900
Tank Heaters - external resistance heaters		$	500	500
Pumps - 2 x centrifugal, lined	2	$	6,400	6,200
Di water storage tank - 7,500 gal plastic tank	1	$	7,500	7,500
DI water production system, 15000 gpd system	1	$	25,000	25,000
Balance of Plant (storage) Equipment, 25%		$	35,625	22,400
Sub-total Purchased Equipment Cost		$	178,125	112,000
Freight and Taxes (8%)		$	14,250	8,960
Total Purchased Equipment Cost		$	192,375	120,960
Installation Costs (equipment installation)		$	48,094	30,240
Indirect Installation Costs (engr, office, etc.)		$	4,809	3,024
Total Installation Costs		$	52,903	33,264
Total Installed Cost		$	245,278	154,224
Administrative Costs (Office, permitting, trng, etc.), ~10% of installed cost		$	24,528	15,422
Total Capital Investment		**$**	**269,806**	**169,646**
Annual Operating Costs				
Labor		$/yr	8,760	8,760
Utility costs		$/yr	2,500	2,500
Subtotal, Operating Costs		$/yr	11,260	11,260
Overheads		$/yr	16,890	16,890
Capital Recovery (3-yr, 10%)		$/yr	108,493	68,217
Annualized Total Cost		**$/yr**	**136,643**	**96,367**
		$/ton	**22**	**16**
		$/gal	**0.03**	**0.02**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor		
	Inerest Rate, i		10%
	Time Period in Years, n		3
	Capital Recovery Factor, CRF		0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.		
3	Equipment costs, except for DI water system, were estimated using vendor information and a proprietary web-based Chemical Process Engineering software. Costs are order-of-magnitude nature.		
4	Number of terminals actively dealing with SCR-urea		650
5	Annual national solid granular urea consumption, tons		**4,000,000**
6	Avg. annual solid urea throughput, tons/terminal/year		6154
		tons/day/terminal	16.8
7	Average solid urea storage capacity, tons/terminal		118
8	SCR Urea throughput per terminal, gal/day		11,392
		gal/yr	4,160,852
9	Average solid urea storage tank capacity, tons/terminal		50
10	Average liq. SCR-urea storage tank capacity, gal/terminal		7,500

Blending & Storage Costs @ Terminal/Plant Level Basis: 1,000,000 tons				
	Qty	Units	Cost	
Capital Costs				
Urea Purity			**High**	**Low**
Purchased Equipment				
Storage hoppers for solid urea - lined,25 ton (1000 ft3) cap. each	2	$	63,600	21,200
Transfer equipment - screw feeders, lined		$	2,400	2,400
Liq. SCR-urea storage tanks, lined, 7500 gal	1	$	25,700	16,100
Agitators/Stirrer - lined, 10 HP		$	8,000	6,900
Tank Heaters - external resistance heaters		$	500	500
Pumps - 2 x centrifugal, lined	2	$	6,400	6,200
Di water storage tank - 7,500 gal plastic tank	1	$	7,500	7,500
DI water production system, 15000 gpd system	1	$	25,000	25,000
Balance of Plant (storage) Equipment, 25%		$	34,775	21,450
Sub-total Purchased Equipment Cost		$	173,875	107,250
Freight and Taxes (8%)		$	13,910	8,580
Total Purchased Equipment Cost		$	187,785	115,830
Installation Costs (equipment installation)		$	46,946	28,958
Indirect Installation Costs (engr, office, etc.)		$	4,695	2,896
Total Installation Costs		$	51,641	31,853
Total Installed Cost		$	239,426	147,683
Administrative Costs (Office, permitting, trng, etc.), ~10% of installed cost		$	23,943	14,768
Total Capital Investment		**$**	**263,368**	**162,452**
Annual Operating Costs				
Labor		$/yr	8,760	8,760
Utility costs		$/yr	2,500	2,500
Subtotal, Operating Costs		$/yr	11,260	11,260
Overheads		$/yr	16,890	16,890
Capital Recovery (3-yr, 10%)		$/yr	105,904	65,324
Annualized Total Cost		**$/yr**	**134,054**	**93,474**
		$/ton	**87**	**61**
		$/gal	**0.13**	**0.09**

Assumptions:

1	Estimate Equivalent Level Cost using the Capital Recovery Factor	
	Inerest Rate, i	10%
	Time Period in Years, n	3
	Capital Recovery Factor, CRF	0.402
2	**Lined** equipment implies, lined with polyfluorocarbon polymers like teflon, etc.	
3	Equipment costs, except for DI water system, were estimated using vendor information and a proprietary web-based Chemical Process Engineering software. Costs are order-of-magnitude nature.	
4	Number of terminals actively dealing with SCR-urea	650
5	Annual national solid granular urea consumption, tons	1000000
6	Avg. annual solid urea throughput, tons/terminal/year	1538
	tons/day/terminal	4.2
7	Average solid urea storage capacity, tons/terminal	29
8	SCR Urea throughput per terminal, gal/day	2,848
	gal/yr	1,040,213
9	Average solid urea storage tank capacity, tons/terminal	50
10	Average liq. SCR-urea storage tank capacity, gal/terminal	7,500

COST ESTIMATION FOR WATER INJECTION

Basis	**gpd**	**30000**	**15000**	**100**	**250**	
	gpm	**21**	**10**	**0.1**	**0.2**	
	TERMINAL LEVEL			**RETAIL LEVEL**		
	Units	**Cost**				
Purchased Equipment						
Membrane-based DI production system	$	15,000	25,000	2,500	2,500	
Sub-total Purchased Equipment Cost	$	15,000	25,000	2,500	2,500	
Freight and Taxes (8%)	$	1,200	2,000	200	200	
Total Purchased Equipment Cost	$	16,200	27,000	2,700	2,700	
Installation Costs (equipment installation)	$	4,050	2,700	270	270	
Indirect Installation Costs (engr, office, etc.)	$	5,405	5,054	5,005	5,005	
Total Installation Costs	$	9,455	7,754	5,275	5,275	
Total Capital Investment	$	25,655	34,754	7,975	7,975	
Annual Costs						
Labor	$/yr	17,520	17,520	2,190	2,190	
Electricity Cost	$/yr	686	343	2	6	
Capital Recovery	$/yr	10,316	13,975	3,207	3,207	
Annualized Total Cost	**$/yr**	**28,522**	**31,838**	**5,399**	**5,403**	
	$/gal-blended	0.00	0.01	0.15	0.06	

Ref:

1 CHAPTER 6, Sec. 6.1 and 6.2 ACT Document - NOx Emissions from Stationary Gas Turbines EPA-453/R-93-007

2 Discussions with Dr. Anurag Mairal, Chief Process Engineer, Membrane Technology & Research, INc.

3 Estimate Equivalent Level Cost using the Capital Recovery Factor

Inerest Rate, i	10%
Time Period in Years, n	3
Capital Recovery Factor, CRF	0.402114804

Appendix E. Potential Spill Evaluation for Selected Pathways

Table E-1. Potential Spill Evaluation — Pathway 1

Distribution Component	Urea Form	Potential Spill Size*	Potential Spill Impacts	Cleanup Options
1A: Granular Urea Import Ship	Granular	Assuming average urea shipping vessel filled to capacity with solid urea loses its entire cargo: 44,000 tons (40,000 metric tons)	Although urea is not listed under DOT regulations as a marine pollutant, a large marine spill of granular urea would likely effect marine life in the form of fishkills. Depending on proximity to shore and/or dynamics of ocean currents, estuaries and associated plant and animal life may be affected.	None known; natural attenuation.
1B: Unloading at port terminal	Granular	Urea will be transported in shipping containers off of the import ship. Assuming entire container volume spilled while unloading: 250 to 300 tons	Granular urea spilled during port terminal unloading may either affect the marine environment or the port terminal area. Fishkills may occur with marine spills. Soil, and ultimately ground- and surface-water will be impacted if the spill isn't contained and collected promptly.	Due to the industrial nature of most port terminals, the granular urea would most likely be deposited on a paved, impermeable surface and be readily collected. Collection for recycling or salvage, followed by washing of the affected area is recommended.
1C: Truck/rail transport to Storage Terminal	Granular	If transported by rail, entire SCR-urea shipment could be spilled in case of derailment: 10,000 tons: 95 cars max, 105 tons/car. By truck: 25 tons (loaded truck capacity)	Granular urea spilled during truck/rail transport may affect soil, and ultimately ground- and surface-water if the spill isn't contained and collected promptly.	If spill occurs to permeable soils, urea should be collected promptly. If spill occurs on an impermeable surface, the granular urea is readily collected for recycling or salvage. Washing of the affected area is recommended.
1D: Storage at terminal	Granular and aqueous	If the dump trucks used to transfer shipment to stockpile or silo spill the entire load: max. load of 25 tons.	Granular and aqueous urea spilled during storage may impact soil and ultimately ground- and surface-water if the spill isn't contained collected promptly.	Due to the industrial nature of most storage terminals, the granular urea would most likely be deposited on a paved, impermeable surface and be readily collected. Aqueous urea should be contained and collected.
1E: Blending at terminal	Aqueous	If the blending and storage units spill their entire capacity: 50,000 gallons. Dump truck transferring urea liquor to blending unit holds: 25 tons	A spill of aqueous urea to permeable soils would impact soil and ultimately ground- and surface-water.	If spill occurs to permeable soils, none are known. If spill occurs to an impermeable surface, containment, absorption and disposal of aqueous urea are recommended, followed by washing of the affected area.
1F: Loading for transport	Aqueous	7,800 gallons (truck capacity)	See 1E, above.	See 1E, above.
1G: Truck transport to truck-stop	Aqueous	7,800 gallons (truck capacity)	See 1E, above.	See 1E, above.
1H: Unloading at truck-stop	Aqueous	7,800 gallons (truck capacity)	See 1E, above.	See 1E, above.
1I: Storage at truck-stop	Aqueous	If the entire storage tank spills: 7,500 gallons (storage tank capacity)	Uncontained spills of aqueous urea from above- or underground-storage tanks may impact soils, and ultimately ground- and surface-water.	See 1E, above. Identification and cleanup of aqueous urea spilled from underground storage tanks may be extremely difficult.
1J: Dispensing	Aqueous	Less than 50 mL	See 1E, above.	See 1E, above.
1K: On-board application storage	Aqueous	13 gallons (SCR-urea tank capacity)	See 1E, above.	See 1E, above.

*In all tables, "tons" refers to short tons (2,000 lb). 1 short ton = 0.91 metric tons

Table E-2. Potential Spill Evaluation — Pathway 4

Distribution Component	Urea Form	Potential Spill Volume	Potential Spill Impacts	Cleanup Options
4A: Granular Urea Plant	Granular	If transported by rail, entire SCR-urea shipment could be spilled in case of derailment: 10,000 tons: 95 cars max, 105 tons/car. By truck: 25 tons (loaded truck capacity)	Granular urea spilled during truck/rail transport may affect soil, and ultimately ground- and surface-water if the spill isn't contained and collected promptly.	Due to the industrial nature of most urea plants, the granular urea would most likely be deposited on a paved, impermeable surface and be readily collected. Collection for recycling or salvage, followed by washing of the affected area is recommended.
4B: Truck/rail transport to Storage Terminal	Granular	See above.	Granular urea spilled during truck/rail transport may affect soil, and ultimately ground- and surface-water if the spill isn't contained and collected promptly.	If spill occurs to permeable soils, urea should be collected promptly. If spill occurs on an impermeable surface, the granular urea is readily collected for recycling or salvage. Washing of the affected area is recommended.
4C: Storage at terminal	Granular	If the dump trucks used to transfer shipment to stockpile or silo spill the entire load: max. load of 25 tons.	Granular and aqueous urea spilled during storage may impact soil and ultimately ground- and surface-water if the spill isn't contained and collected promptly.	Due to the industrial nature of most storage terminals, the granular urea would most likely be deposited on a paved, impermeable surface and be readily collected. Aqueous urea should be contained and collected.
4D: Blending at terminal	Aqueous	If the blending and storage units spill their entire capacity: 50,000 gallons. Dump truck transferring urea liquor to blending unit holds: 25 tons	A spill of aqueous urea to permeable soils would impact soil and ultimately ground- and surface-water.	If spill occurs to permeable soils, none are known. If spill occurs to an impermeable surface, containment, absorption and disposal of aqueous urea are recommended, followed by washing of the affected area.
4E: Loading for transport	Aqueous	7,800 gallons (truck capacity)	See 4D, above.	See 4D, above.
4F: Truck transport to truck-stop	Aqueous	7,800 gallons (truck capacity)	See 4D, above.	See 4D, above.
4G: Unloading at truck-stop	Aqueous	7,800 gallons (truck capacity)	See 4D, above.	See 4D, above.
4H: Storage at truck-stop	Aqueous	If the entire storage tank spills: 7,500 gallons (storage tank capacity)	Uncontained spills of aqueous urea from above- or underground-storage tanks may impact soils, and ultimately ground- and surface-water.	See 4D, above. Identification and cleanup of aqueous urea spilled from underground storage tanks may be extremely difficult.
4I: Dispensing	Aqueous	Less than 50 mL	See 4D, above.	See 4D, above.
4J: On-board application storage	Aqueous	13 gallons (SCR-urea tank capacity)	See 4D, above.	See 4D, above.

Table E-3. Potential Spill Evaluation — Pathway 8

Distribution Component		Urea Form	Potential Spill Volume	Potential Spill Impacts	Cleanup Options
8A:	Aqueous Urea Plant	Aqueous	If transported by rail, entire SCR-urea shipment could be spilled in case of derailment: 10,000 tons: 95 cars max, 105 tons/car. By truck: 7,800 gallons (loaded truck capacity)	A spill of aqueous urea to permeable soils would impact soil and ultimately ground- and surface-water.	If spill occurs to permeable soils, none are known. If spill occurs to an impermeable surface, containment, absorption and disposal of aqueous urea are recommended, followed by washing of the affected area.
8B:	Truck/rail transport to Storage Terminal	Aqueous	See above.	See 8A, above.	See 8A, above.
8C:	Storage at terminal	Aqueous	Terminal capacity: 50,000 gallons;	See 8A, above.	See 8A, above.
8D:	Blending at terminal	Aqueous	If the blending and storage units spill their entire capacity: 50,000 gallons. Dump truck transferring urea liquor to blending unit holds: 25 tons	See 8A, above.	See 8A, above.
8E:	Loading for transport	Aqueous	7,800 gallons (truck capacity)	See 8A, above.	See 8A, above.
8F:	Truck transport to truck-stop	Aqueous	7,800 gallons (truck capacity)	See 8A, above.	See 8A, above.
8G:	Unloading at truck-stop	Aqueous	7,800 gallons is (truck capacity)	See 8A, above.	See 8A, above.
8H:	Storage at truck-stop	Aqueous	If the entire storage tank spills: 7,500 gallons (storage tank capacity)	Uncontained spills of aqueous urea from above- or underground-storage tanks may impact soils, and ultimately ground- and surface-water.	See 8A, above.
8I:	Dispensing	Aqueous	Less than 50 mL	See 8A, above.	See 8A, above.
8J:	On-board application storage	Aqueous	13 gallons (SCR-urea tank capacity)	See 8A, above.	See 8A, above.

Table E-4. Potential Spill Evaluation — Pathway 9

	Distribution Component	Urea Form	Potential Spill Volume	Potential Spill Impacts	Cleanup Options
9A:	Aqueous Urea Plant	Aqueous	If transported by rail, entire SCR-urea shipment could be spilled in case of derailment: 10,000 tons: 95 cars max, 105 tons/car. By truck: 7,800 gallons (loaded truck capacity)	A spill of aqueous urea to permeable soils would impact soil and ultimately ground- and surface-water.	If spill occurs to permeable soils, none are known. If spill occurs to an impermeable surface, containment, absorption and disposal of aqueous urea are recommended, followed by washing of the affected area.
9B:	Loading for transport	Aqueous	7,800 gallons (truck capacity)	See 9A, above.	See 9A, above.
9C:	Truck transport to blending terminal/ truck-stop	Aqueous	7,800 gallons (truck capacity)	See 9A, above.	See 9A, above.
9D:	Unloading at blending terminal/ truck-stop	Aqueous	7,800 gallons is (truck capacity)	See 9A, above.	See 9A, above.
9E:	Storage at blending terminal/ truck-stop	Aqueous	If the entire storage tank spills: 7,500 gallons (storage tank capacity)	Uncontained spills of aqueous urea from above- or underground-storage tanks may impact soils, and ultimately ground- and surface-water.	See 9A, above.
9F:	Dispensing	Aqueous	Less than 50 mL	See 9A, above.	See 9A, above.
9G:	On-board application storage	Aqueous	13 gallons (SCR-urea tank capacity)	See 9A, above.	See 9A, above.

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